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A STUDY OF THE FRICTION AND ENERGY REQUIREMENTS IN EXTRUDING HAY

by

SIMON AVATES HANN

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "A Study of the Friction and Energy Requirements in Extruding Hay", submitted by Simon Avates Hann in partial fulfilment of the requirements for the degree of Master of Science.

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ABSTRACT

The limited success of the extrusion process for wafering hay is a result of the high energy requirements which put the cost to own and maintain such a machine beyond the reach of most farming operations. Much of this energy is wasted in overcoming the friction between the wafer and the extrusion die.

A laboratory experiment was designed to investigate some of the factors affecting friction and energy requirements in extruding alfalfa, and to test the feasibility of extruding a satisfactory product with less energy. To accomplish these objectives, data for friction, energy and wafer durability were recorded for various levels of moisture content in the alfalfa, extrusion pressure, back pressure in the die and binders. The experiment was performed on a single-shot hydraulic wafering press which approximates the extrusion-type process.

The following results and conclusions were obtained from an analysis of the data.

1. The ease with which alfalfa passed through the extrusion die diminished with higher levels of extrusion pressure and back pressure due to increased friction in the die. At the highest extrusion pressure (5800 psi) the friction was a maximum when the hay, without a binder, contained around 20 percent moisture. The application of binders contributed to additional increases in friction.
2. The initial compression of the hay sample requires less energy than is required to extrude the wafer. Reductions in the portion

of the total wafering energy attributed to extrusion (friction) are best achieved by decreasing extrusion pressure.

3. Wafers of very good quality (durability ratings in excess of 90 percent) were extruded with specific energies as low as 5 horsepower-hours/ton of wafers.

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1. INTRODUCTION AND OBJECTIVES

Wafering has been an alternative system for processing alfalfa since the late 1950's. With wafers the harvesting, storing and feeding of alfalfa can be completely mechanized, an obvious advantage over most other hay harvesting systems. Also the reduced storage costs and the improved quality of wafered hay gives it an advantage over loose or ensilaged hay. The acceptance of the wafering process by individual farmers and farming corporations, however, has not been as widespread as was initially anticipated when wafering was first introduced. The numerous advantages associated with the product have been more than offset by the drawbacks associated with the process itself.

Most wafering machines employ an extrusion-type process. Inherent in this process are high levels of friction encountered in the wafering die. In order to overcome the friction and extrude the material through the die, extremely high pressures are required. To develop high pressure requires a large amount of energy and also a size and quality of machine that only a few farming enterprises can afford to purchase.

Because of the limited success of the extrusion process, other methods of wafering have been investigated. Also the possibility of using the extrusion process to form durable wafers from materials other than alfalfa has been considered. However the causes of friction and high energy requirements in extruding hay have received very little attention; and the feasibility of extruding a satisfactory product with less energy has not been established, therefore, the

objectives of this study were:

1. to obtain information on how the following factors affect the friction associated with the extrusion of alfalfa hay:
    a) moisture content,
    b) resistance due to die characteristics,
    c) extrusion pressure, and
    d) binders;
2. to establish the division of energy between the compression stage and the extrusion stage of wafering for varying levels of extrusion pressure and hay moisture content; and
3. to determine a wafering efficiency (total wafering energy required per change in durability) for all possible treatment combinations and use this in conjunction with the absolute values of energy and durability in recommending optimum operating conditions for a wafering process.

2. LITERATURE REVIEW

2.1 Definitions.

The following terminology is useful to describe wafering (2).

Wafer: A wafer is an agglomeration of unground ingredients in which some of the fibres are equal to or greater than the length of the maximum cross-section of the agglomeration. Wafers can be any geometric shape; however the most popular shapes are cubes and cylinders.

Pellet: A pellet is an agglomeration of individual ground ingredients or a mixture of such ingredients, commonly used for animal feeds. Pellets are usually cylindrical in shape with a diameter of less than 3/4 of an inch.

Moisture Content: Percent of moisture content is computed on a wet basis.

Bulk Density: The wafers or pellets are weighed in a cylindrical container with an inside diameter of 15 inches and an inside height of 19.5 inches. The net weight in pounds is multiplied by 0.5 to yield density in lb per cu ft. The wafer quality is determined as follows:

i. very good for bulk density greater than 30 lb/cu ft,

ii. good for bulk density between 25 and 30 lb/cu ft, and

iii. poor for bulk density less than 25 lb/cu ft.

Durability: The durability is obtained by tumbling a test sample for 3 minutes at 13 rpm in a rectangular cage rotated about its diagonal axis as shown in Figure 1. After the test, the total weight of the wafers which are greater than 20 percent of their original weight is divided by the original weight of the test

sample. This quotient, when expressed as a percentage, is the durability rating. There is also a durability index which indicates the extent to which cubes break into smaller pieces however, to be consistent, only the durability rating will be used. Based on durability, the quality of wafers is defined as follows:

	Durability Rating 0 - 100
Very good	90 to 100
Good	80 to 90
Fair	70 to 80
Poor	60 to 70
Unsatisfactory	below 60

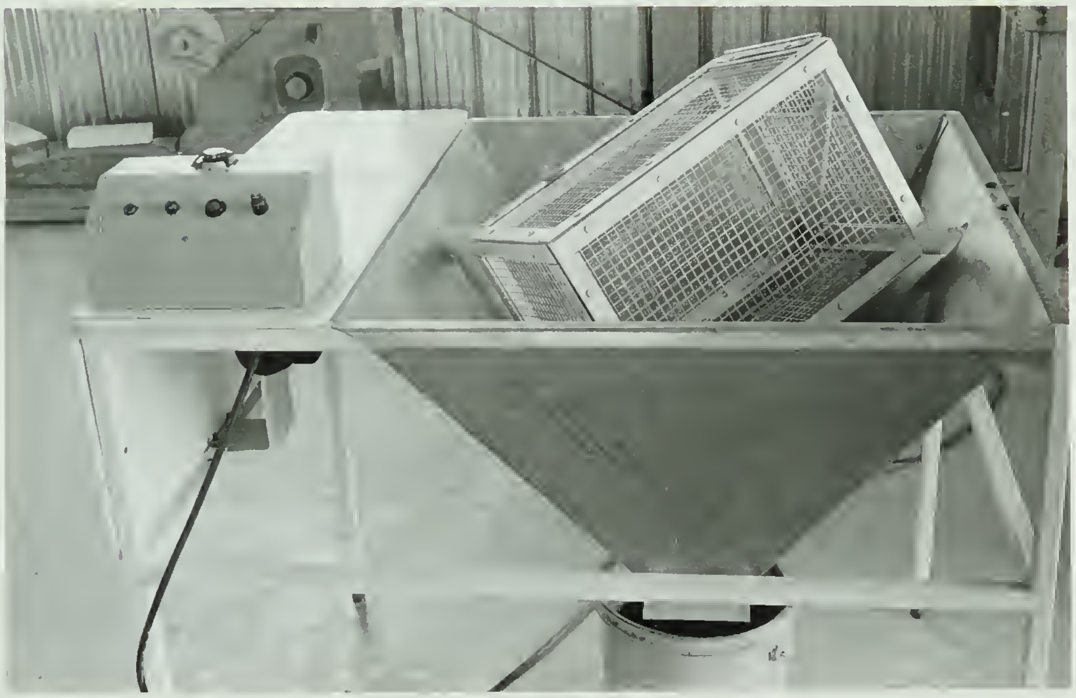

Figure 1. Wafer durability tester.

2.2 <u>The Methods of Wafering.</u>

There are four basic systems which have been investigated so far for wafering hay.

1. The "plunger" type is much like the conventional baler but operates at much higher pressures and has a multitude of smaller outlets.
2. With the "nip-roll" type, hay is forced between two rollers and is either pressed into continuous ribbons which are then cut up into suitable chunks, or pressed into indentations in the rollers, forming briquets.
3. With the "rolling-compressing" technique, hay is fed into the channel formed by four axially parallel or skewed rollers where the hay is rolled and compressed into a rope-like form and subsequently cut into wafer-length units.
4. The "roller-extrusion" system uses a press wheel rolling around the inner surface of a die ring to force material radially outward through die openings. The roller-extrusion system is the most widely used method of wafering hay today. It is found in practically all pelleting mills and in most of the commercial stationary and field wafering machines.

Despite the popularity of the roller extruders, they consume considerably more energy than the other three systems mentioned above (21, 35, 36). This is primarily due to the excessive amount of friction which is inherent with the extrusion process. It appears likely that unless some modifications can be made to this current process to substantially reduce the friction and the energy requirements, one or more of the other three alternatives may soon become popular.

2.2.1 The Plunger System.

The plunger system may use the open-end extrusion dies or the closed-end cylinders. The open-end extrusion operation is very similar to the roller-extrusion system and will be discussed later. The formation of wafers in the closed-end cylinders has been studied in most detail by the researchers. It is an operation that can easily be simulated in the laboratory and in some cases the test results apply equally well for other methods of wafering.

Much of the research with closed-end dies has dealt with optimizing the various input variables of wafering to produce a product with sufficient density and durability. The general consensus is that hay with a moisture content of about 20 percent produced the most durable wafer while 10 to 15 percent hay gave the best wafer density (13, 36, 39, 41). Reducing the hay length improves wafer density but has a negative affect on durability (11, 26, 44), however, the maceration (crushing or shredding) of hay improves both the density and the durability of the wafer (27, 36). Rehkugler (41) and Pickard et al (36) found that wafer density decreased with increased maturity of the hay.

The effects of process variables on wafer formation are very well understood and are conceded by most researchers. Increases in the applied pressure, the length of time that the wafer is held under pressure or the temperature of the forage will always benefit wafer density and durability. The optimum levels for these variables, which would yield a feasible closed-end die process, are: 2000 psi pressure, 5 seconds hold time and 200^{o}F die temperature (9, 25, 39).

Tests which have been conducted on a piston and closed-end

cylinder apparatus indicate that this method of wafering would require in the order of 5 horsepower-hours per ton of wafers (7, 40). This is approximately one third of the energy required to form wafers via the roller-extrusion method (23), however, the closed-end die arrangement is not as efficient as test results tend to suggest. The process is not quite so attractive when the following mechanical problems (40) are considered:

1. removing the formed wafer from the die
2. controlling the feed rate so that the required amount of hay is placed in each die
3. adopting a basically cyclic process to a continuous-flow system.

The energy requirement for forming wafers is directly proportional to the applied pressure (7). Therefore if the pressure can be reduced without a reduction in wafer quality, it will mean a similar drop in the energy requirement. Any alteration in the variables discussed earlier which result in improvements in the wafer density or durability (except increases in pressure) can also be utilized to allow for a reduction in the applied pressure and thus a lowering of the energy requirements.

The energy requirement of a plunger system, operating with a constant-stroke ram and a closed-end die, is greatly affected by the charge-size of material being compressed (22, 26). An increased charge-size is caused by a higher feed rate or an increased percentage of moisture in the forage, both of which result in a larger volume to be compressed in the die. This larger volume produces a higher pressure on the ram and thus raises the energy required.

Moisture by itself was found to have an additional effect on the energy requirements of a closed-end die system. Bellinger and McColly (7) found that the force or energy required to eject a wafer from the die increased significantly as the moisture content of the hay was decreased. The moisture provides a lubricating effect when it is present at higher levels thus aiding in the ejection of wafers. Since the energy required to eject the wafers can reach as much as 10 percent of the total energy for the system (40), this influence of moisture cannot be ignored.

The plunger system has not yet been developed to the extent that it is a commercially viable alternative to the extrusion process. However, as a research tool, the plunger and closed-end die apparatus has been instrumental in establishing the behaviour of forage material when compressed into a wafer form.

2.2.2 The Nip-Roll System.

The nip-roll system, like the plunger system, contains several desirable features for wafering hay; but still not enough to replace the popular method of roller-extrusion. Alfalfa can be rolled into briquets throughout the moisture range of 10 to 30 percent, however, the easiest moisture range to work in is 14 to 19 percent (21). The moisture content is not nearly as critical with briquetting as it is with some other modes of agglomeration. Processing the crop at these higher levels of moisture means less time and money spent drying prior to wafering as well as preserving a greater quantity of carotene and xanthophyll (31). The only hesitation towards briquets with more than 15 percent moisture is the risk of spoilage in storage. It is always more efficient to dry the hay to a safe level while it is still

in the loose form rather than after it has been compressed into a dense wafer (24).

The energy required to briquet one ton of alfalfa is roughly half the energy required to process one ton of alfalfa in the conventional extrusion machines (21). This is because the compression of forage material is attained more efficiently between two nip-rolls than it is in an extrusion die. Alfalfa fibres, in particular, readily lend themselves to pressing and rolling but not to sliding stresses and shear. So in a rolling press, where there are no undue shearing stresses, the heat of processing will be considerably lower than in an extrusion die. This means both economic and nutritional savings.

Any fluctuation in the energy requirements for wafering with nip-rolls is primarily due to a change in force between the two rollers (29). Higher forces brought about by either a reduction in clearance or a higher feed rate, require more energy.

Where the performance of the nip-roll system becomes doubtful, is in producing wafers of consistently good quality. Dobie (16) claims the major cause for low quality briquets is the insufficient dwell time (less than 0.5 sec) under compression between the nip-rolls. For material as resilient as forage crops, a fairly long dwell time is required to ensure that the wafer holds its original shape as much as possible.

2.2.3 The Rolling-Compressing System.

The rolling-compressing system is a relatively new innovation for wafering hay. This system appears to have solved many of the problems currently plaguing most other methods of wafering. The following is a list (34) of some of the advantages it has over the

existing wafering techiques:

1. Rolling-compressing wafering is applicable to grasses as well as legumes, because interlock binding plays such an important role.
2. Material from fresh cut to storage-moisture content can be wafered equally well by this method. (The compression applied by the four boundary rollers can squeeze a great deal of water out of fresh cut hay (33), reducing moisture content to as low as 40 percent.)
3. Chopping the hay is not necessary as long stems are preferred.
4. The energy requirements are quite low (10 hp-hr/ton) (35) for the same reason as mentioned in the nip-roll system.
5. Capital costs could be relatively low compared to other wafering systems.

The disadvantages of the rolling-compressing system are:

1. The process is not always capable of tucking in loose exterior fibres which causes the wafer to have a somewhat wooly appearance, especially at lower moisture contents (34).
2. Present technology for drying and storing is not adequate for wafers that are produced with high moisture contents.

The drying should be made easier, however, with rolled-compressed wafers. These wafers, which are formed with initial fibres parallel to the roller axes and with the balance of the fibres rolled around the axial fibres, are conducive to air flow which in turn facilitates drying (35).

A rolling-compressing wafering machine has potential in the wafering industry. It can produce a product of satisfactory density

and durability regardless of what the moisture content might be; and the energy required is reasonable as well. This system can be adapted equally well to a silage operation, where wafers of 50 to 70 percent moisture are produced and stored in silos, or to a dry haying operation, where wafers of approximately 15 percent moisture are produced (10, 33). In addition, the rolling-compressing process yields a high protein exudate from crops of high moisture content. This exudate could be collected at little extra cost or energy and then dried in a separate process producing a valuable protein supplement (12).

2.2.4 <u>The Roller-Extrusion System</u>.

The research with extrusion systems revealed some of the same trends as were found in the closed-end die experiments. The moisture content of the hay for producing satisfactory wafers should be less than 15 percent (37). Early maturity hay with less fibrous content, forms a better wafer than late maturity hay (32). Waelti and Dobie (46) found that increased levels of the three process variables - pressure, hold time under pressure and temperature - improved wafer quality in much the same way as was established by Reece (39) using a closed-end die apparatus.

The research by Dobie et al was carried out on a single-shot, extrusion-type cubing press. Their primary concern was with wafer quality and not energy requirements. They studied the wafering ability of such materials as barley straw (17), rice straw (46), moist alfalfa (19), wood shavings (18) and complete ration alfalfa-concentrate mixtures for cattle (20). In most cases these materials would only form wafers through the use of bonding agents; and in the case of moist alfalfa, a preservative to prevent mould in storage

was also required.

In the area of energy requirements for the extrusion process, Witte (47) made some significant contributions. He studied the relationship between die geometry and the energy required for wafering as affected by moisture content and condition of the hay. He was able to conclude that the optimum energy efficiency (the lowest total wafering energy required per unit change in density) was obtained with an angle of die convergence of 3.5 inches/foot. Witte also observed that the total wafering energy, maximum pressure required and final wafer density decreased noticeably as the moisture content increased from 15 to 25 percent.

The total wafering energy, referred to above, is the total of compression energy and extrusion energy. The former is of the same magnitude as that obtained using a closed-end die system. The latter can be expected to exceed the energy of compression (36) due to the friction involved. This extra energy for extrusion will, of course, result in higher density wafers than can be achieved in a closed-end die operating under identical conditions.

Numerous attempts have been made to reduce the overall energy requirements of pelleting and wafering operations to that required for conventional haymaking systems. Experiments have indicated that the wafering energy for roller-extrusion systems can be reduced by:

1. increasing the die cross-sectional area (45),
2. reducing the thickness of the die (4),
3. using a frictionless coating on the die walls (47),
4. reducing the particle length of the forage material (8), and
5. decreasing the moisture content of the hay below 15 percent (3).

The first three improvements, however, could reduce wafer durability. Obviously, some optimum level of these factors is required to reduce the energy requirements and still maintain good durability. Similarly, there is an optimum particle size which will not require excessive size reduction and can still be wafered satisfactorily with a minimum of energy.

The optimum levels, arrived at by John Deere and Company (23) for the factors considered above are:

1. area of the die opening, 1 1/4 inch square
2. length of the die, 6 inches
3. chromeplated die surfaces
4. theoretical length of cut, 1 3/8 inch
5. internal moisture content, less than 12 percent (with sufficient water added to the hay prior to wafering to bring the moisture content up to 12 to 15 percent)

Operating under these conditions, the John Deere '400' Cuber producing 8 tons of wafers per hour still requires 27 hp-hr/ton or more than ten times the energy required for baling (42). Sixty-five percent of this energy is required for extruding the hay through the die (23). This portion of the total energy requirements has got to be reduced considerably in order for the roller-extrusion system of wafering to be competitive with other existing methods of haymaking, especially now that energy is at a premium.

2.3 The Problem of Moisture Content.

For wafering, alfalfa hay should be field cured or artificially dried to 12 percent moisture content, with surface moisture added immediately prior to wafering to provide a final moisture content of

15 percent (19). This practice is, in fact, followed quite closely in most wafering operations and normally results in a better product than wafering with 15 percent internal moisture. The free surface moisture can activate the natural soluble adhesives associated with the alfalfa plant more efficiently than internal moisture, which is usually trapped in the plant cells (23).

Wafers that are formed with hay of less than 10 percent moisture are brittle and therefore tend to be less durable (43). Under high extrusion pressures, the stems are flattened to such an extent that they crack and break into pieces, thus reducing their interlocking strength, but lower extrusion pressures are not capable of compacting the material sufficiently. This is due to the lack of lubricating moisture which hinders the particle movement and the reduction of pore space (42).

If there is too much moisture in the hay, the water, being incompressible, prevents adequate crushing of the stems and breakdown of the stem structure. Thus, very little natural adhesive is released from the plant material and the wafer will not hold together very well (27). Huang (27) found that macerating the hay previous to wafering would expose the adhesive protoplasm and facilitate the production of durable, high moisture wafers with lower pressures. This pretreatment would be attractive if an efficient method could be found for drying the moist wafers for safe storage.

2.4 The Use of Binders.

Most of the experiments with binders (11, 17, 19, 20, 46) have dealt with improving the wafering ability of materials other

than good quality alfalfa. It is well accepted by Dobie et al (17) that under normal wafering conditions, good quality alfalfa will produce a dense, durable wafer without the need for a binder. Many other materials like straw and grass, however, do require some form of bonding agent to produce a product sufficiently durable for handling.

The method of applying binders has received considerable study as well. Dobie et al (17) concluded that binders should be applied dry unless they can be made into water solutions of at least 20 percent binder, so that sufficient binding strength is present in the wafer without the addition of too much water. Provided the amount of water required to activate the binder does not exceed 3 percent of the wafer weight, there should be little detrimental effect on wafer durability (46).

Under the Canadian Food and Drug Regulations (1), the maximum allowable concentration of most chemical binders in wafers for animal consumption is limited to 4 percent of the wafer weight. However some of the more toxic binding agents like Orzan, a lignin extract, are limited to 3 percent by weight (15).

Of the numerous binders mentioned in the literature, Orzan and Bentonite are two that have been used commercially in wafering and pelleting low quality forages. Orzan is primarily ammonium lignin sulfonate and is used most effectively in the liquid form with 50 percent water (15, 17). Bentonite is dry, finely ground and sieved Montmorillonite clay which is usually applied in a wafering process at a rate of 2 percent by weight with 4 percent of water spray added for activation (6). Dobie et al (19) found very little

difference between Orzan and Bentonite for improving the durability of alfalfa wafers at low moisture contents. However for moisture contents greater than 20 percent, Orzan proved to be much superior. The possibility of using a binder to obtain good quality alfalfa wafers with less wafering pressure apparently has not been investigated. This method for reducing the energy requirements in wafering alfalfa is a promising alternative.

2.5 Summary of Literature Review.

Several varied methods of wafering hay have been created and analyzed. The roller-extrusion system was adopted commercially because, at the time, it was the only system which incorporated both a continuous flow process and the ability to consistently form a dense, durable product (17). The recently developed rolling-compressing technique (30, 33, 34, 35) displays the same desirable characteristics as well as additional advantages associated with low energy requirements and operating over a wide range of moisture contents. For the existing roller-extrusion system to remain competitive in the wafering industry, more research should be directed towards the energy aspects of extruding hay. (Apparently, most of the experiments with the extrusion technique have dealt with the wafering ability of low quality forages (4, 17, 19, 20, 46) as affected by various levels of forage and process variables.)

This report will investigate some of the causes of high energy requirements in extruding alfalfa, and propose several schemes which manufacturers and operators of roller-extrusion-type wafering machines might consider to attain a more energy efficient system.

Possibilities such as using bonding agents, wafering at higher moisture levels, and wafering with less die resistance will be examined for their feasibility in permitting lower wafering energies.

3. DESIGN OF THE EXPERIMENT

There are numerous variables associated with the material to be processed and the process itself, which influence the energy required. These include:

(A) Forage Variables -

1. species
2. maturity
3. internal moisture content
4. leaf:stem ratio
5. particle size

(B) Process Variables -

1. applied pressure
2. hold time under pressure
3. die characteristics (smoothness and geometry)
4. die temperature
5. binders
6. application of steam or water immediately prior to wafering

Alfalfa was the forage species used throughout this study as it is the major crop being wafered today and any new information on a wafering process should pertain to alfalfa first. The internal moisture content of the alfalfa hay was included as a variable in the experiment because it has been a major concern in previous wafering studies and deserves considerable attention in the initial investigations of friction and energy. Preliminary trials indicated that forage maturity, leaf:stem ratio and particle size had a negligible affect on die friction and therefore these factors were deleted from the study.

Extrusion pressure or the pressure applied to the wafer in forcing it through the die determines the basic levels of energy consumed in the process. (All other variables merely cause minor fluctuations of this level.) Extrusion pressure was included therefore to establish different levels of wafering energy and to provide another source of variation for friction and wafer quality.

The time that the wafer is held under pressure in the die (extrusion time) can be an independent variable, however it was allowed to vary in this experiment to provide a measure of die friction. To observe the effects of different rates of extrusion on friction and energy, two levels of die characteristics were included for each treatment. One level was represented by a low back pressure on the wafer while the other was represented by a high back pressure. A low back pressure was established for each level of extrusion pressure to allow the wafer to pass through the die fairly rapidly (approximately 3.5 seconds). A high back pressure was selected to increase the extrusion time to approximately 7 seconds. It was expected, however, that due to the friction effects these extrusion times would vary from one treatment to the next.

There are no provisions in the design of current wafering machines for altering die temperature. To provide a means of heating or cooling the die would increase the cost of the machine considerably. Therefore die temperature was maintained at a constant value throughout the experiment.

The use of binders was included as a factor because its positive effect on wafer quality indicated a possibility for wafering alfalfa at lower energy levels.

The application of steam or water immediately prior to wafering was difficult to carry out accurately when wafering such a small sample of hay at a time and therefore was omitted.

The levels of the various independent variables were as follows:
- extrusion or applied pressure : 1100, 3400 and 5800 psi
- die characteristics or back pressure : low and high
- moisture content of the hay : 10, 20 and 30 percent
- binder used : none, Orzan and Bentonite

The 54 treatment combinations of the above parameters were applied once on one year old alfalfa meal and replicated on current year alfalfa meal.

The range of each variable was chosen to include the current operating conditions of most extrusion-type wafering machines (19) (i.e. extrusion pressure of approximately 5800 psi; extrusion time of approximately 7 seconds; 12 percent moisture content of the hay; and no binder used). The limits on the variables were checked to ensure that there would be a good span in the data for energy, extrusion time and durability. The back pressure initially had three levels. However, the highest level had to be dropped as the extrusion times for particular treatments during the experiment were unreasonably long.

A split-plot experimental design with the two replications was used in making the tests. Binders were treated as main plots in order that other binders or other binder concentrations could be added some time in the future without the necessity of repeating this experiment. The eighteen treatment combinations of moisture content, extrusion pressure and back pressure were then randomized within each main plot.

4. EQUIPMENT

A single-shot hydraulic wafering press capable of simulating an extrusion-type wafering process was designed by the Alberta Department of Agriculture, Edmonton, Alberta and constructed by a local manufacturing company (Figure 2). The press consisted of an upper and lower hydraulicly driven ram moving inside an electrically heated die. The upper ram exerted the extrusion pressure. The lower ram was required for exerting a back pressure in the die, equivalent to the resistance encountered in extrusion caused by the size and smoothness of the die and by the die being full of compacted material. There were pressure regulator valves and pressure gauges for adjusting both the extrusion pressure on the wafer and the back pressure in the die.

To facilitate recording the extrusion pressure continuously and a subsequent determination of the wafering energy, a pressure transducer was put in the line to the high pressure end of the upper cylinder and a rotary potentiometer was set up to measure the upper ram displacement (Figure 3). The pressure versus displacement curves were recorded on an x-y plotter. With the use of a planimeter the area under each curve was obtained and converted into a measurement of energy.

A stopwatch accurate to 0.2 of a second was used to measure the time it took for each wafer to pass through the die (extrusion time).

Wafer durability was determined using standard ASAE wafer durability equipment as shown earlier in Figure 1.

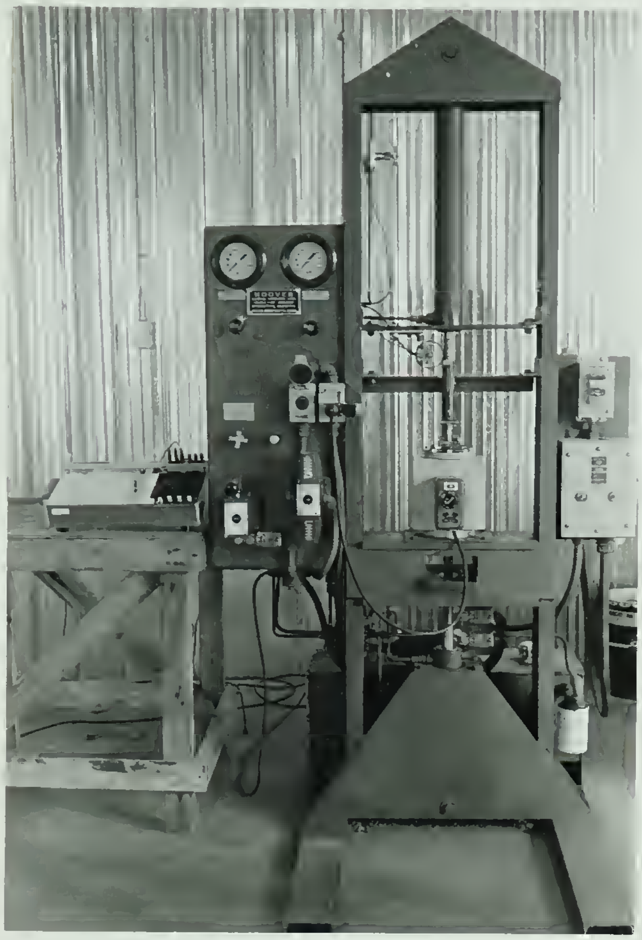

Figure 2: The single-shot hydraulic wafering press used in this experiment.

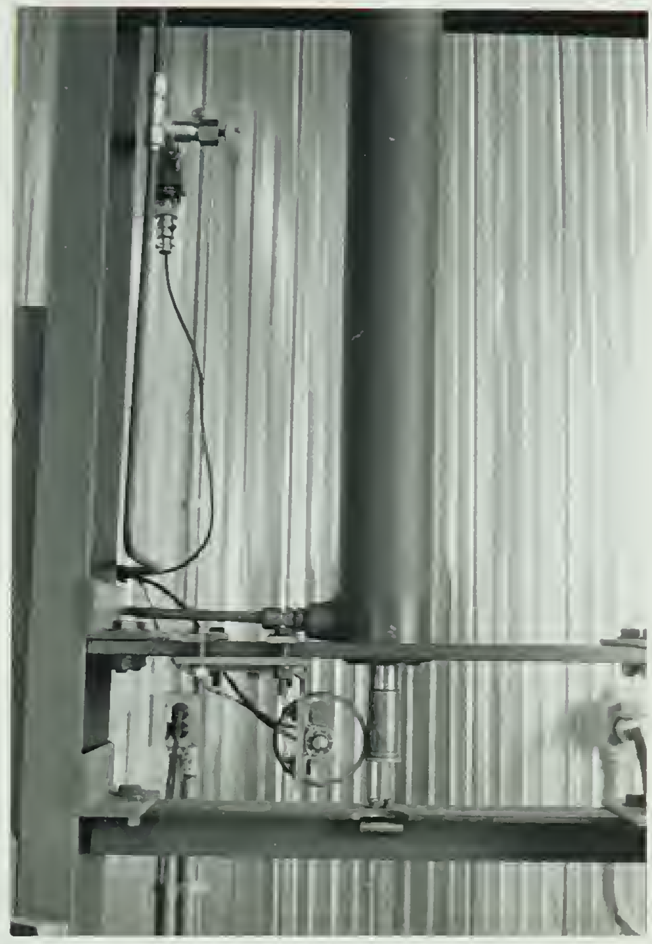

Figure 3: A detailed view of the pressure transducer (top) and the rotary potentiometer (bottom) used in obtaining pressure-displacement curves for the upper ram.

5. EXPERIMENTAL PROCEDURE

5.1 Preparation of Samples.

Two lots of alfalfa meal, for the two replications in the experiment, were obtained from a local pelleting plant. The first lot was field cured hay which had been stored over winter in a stack. This hay had been put through a tub grinder giving it a shredded appearance. The hay had been handled in a dry state and therefore contained large amounts of fine dusty particles and very few whole leaves. The second lot of meal was fresh-cut alfalfa which had been chopped with a harvester.

All the hay was dried to approximately 10 percent moisture (wet basis) and maintained at this level until ready for use. Other moisture contents were obtained by placing 300 grams of the hay at 10 percent moisture in an air-tight plastic bag, and adding enough water to bring the moisture content up to the desirable level. (Refer to Table 1.) The bags of hay were then sealed and stored in a cool room (at around 45°F) for at least forty-eight hours to allow the moisture to be distributed uniformly throughout the sample.

Bonding agents were added to the whole 300 gram sample of 10 percent hay or to the bag full of moistened hay immediately prior to a test. The binders, either Orzan or Bentonite (dry powders), were sprinkled over the hay sample and sprayed with water before mixing, to prevent the binders from sifting to the bottom of the container. The ratio of spray to binder was just sufficient to make a solution, which was 50:50 for Orzan and 67:33 for Bentonite. The proportion of spray plus binder solution in the wafer was always

TABLE 1: PREPARATION OF SAMPLES.

Moisture Content (percent)	Binder	Weight of Water Added (grams)	Weight of Dry Binder Added (grams)	Weight of Spray Added (grams)	Weight of Moist Hay Plus Binder Per Test (grams)	Weight of Moist Hay Plus Binder Per Wafer (grams)
10	None	0	0	0	300	20
	Orzan	0	8	8	316	21.1
	Bentonite	0	5.3	10.7	316	21.1
20	None	38	0	0	338	22.5
	Orzan	38	9	9	356	23.7
	Bentonite	38	6	12	356	23.7
30	None	86	0	0	386	25.7
	Orzan	86	10	10	406	27.1
	Bentonite	86	6.7	13.3	406	27.1

maintained at 5 percent of the final wafer weight. (Refer to Table 1 for exact values.)

To ensure that the treatment effects were the only cause of variation in the results, all wafers contained the same amount of dry hay (18 gms). However, depending on the moisture content and whether or not a binder was used, the actual wafer weights varied between treatments. The weight of material which went into each wafer is also listed in Table 1. There was usually enough material in each large sample to produce fourteen or fifteen individual wafers for a given treatment.

5.2 Operation of Extrusion Press.

The extrusion die shown at D in Figure 4, had to be preheated for at least thirty minutes prior to operation of the press. The die temperature was brought to a constant 175°F for all treatments. It was found that the press performed more consistently if the hydraulic fluid was warmed up as well before commencing any tests. This was achieved by actuating the pump and opening the bleed-off for about ten minutes.

The upper and lower rams were raised simultaneously with the manually operated directional control valve, G. At their upper limits the top ram was almost completely retracted and the lower ram was about one inch from the top of the die. The loading column, C, filled with a sample of hay, was then placed on top of the die and the bottom gate was opened. The upper ram was actuated, which pushed the material out of the loading column down into the die and against the lower ram, compressing the material into a wafer. When the preset

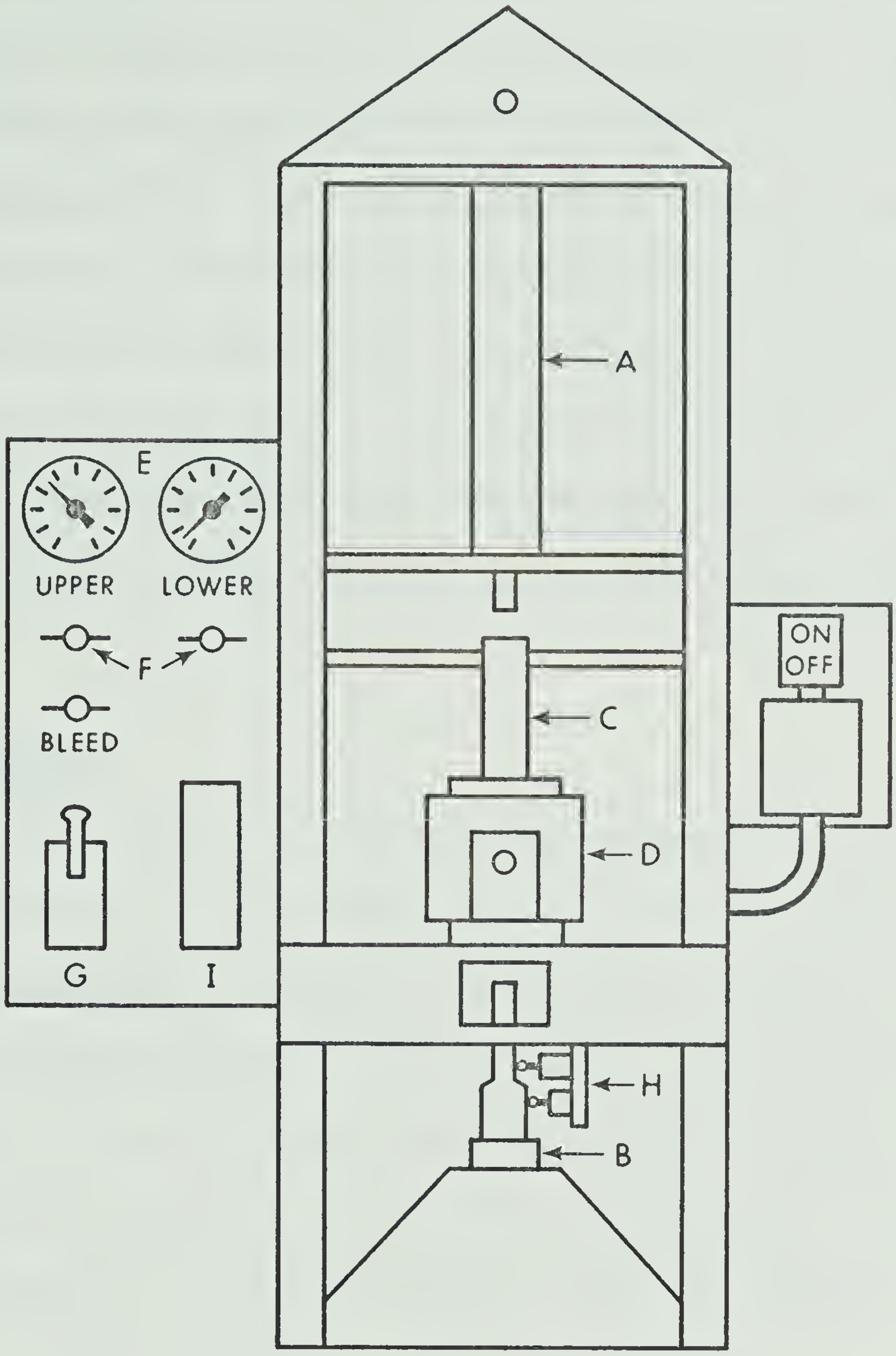

Figure 4: Schematic of wafering apparatus. (A) upper cylinder; (B) lower cylinder; (C) loading column; (D) extrusion die; (E) pressure gauges for upper and lower cylinder; (F) pressure control valves; (G) directional control valve for both rams; (H) microswitches which activate the directional control valve (I) to provide increased retraction speed for the lower ram at the end of extrusion.

extrusion pressure was attained, both rams moved together, downward through the die, keeping constant pressure on the wafer. When the end of the lower ram reached the bottom of the die, a microswitch, H, was triggered and the lower ram retracted at increased speed. Thus, the finished wafer was extruded from the die without back pressure.

The die was cleaned before each treatment to eliminate any effects from the previous runs. Also two or three wafers were formed under a given treatment before measurements were taken. This was to insure that the die and the hydraulic system had reached a steady state.

5.3 Calibrations.

Due to the design of the hydraulic system for the extrusion press, the pressures in the upper and lower cylinders could not be adjusted independently. A change in the pressure setting for one cylinder would automatically cause some change in the pressures for both cylinders. For this reason the pressure control valves, F in Figure 4, were calibrated as a pair and not individually. For each possible combination of extrusion pressure and back pressure, the valve settings for both cylinders had to be adjusted.

The thermostat on the extrusion die was calibrated by filling the die with oil and measuring the oil temperature near the centre of the die.

The pressure transducer was calibrated on the x-y plotter between 0 and 2000 psi using standard pressure equipment. A multiplication factor of 5.6 was used to convert transducer (cylinder) pressures into extrusion pressures.

5.4 Determinations.

5.4.1 Energy.

The x-y plotter was zeroed on both the ordinate and the abscissa before each run. Three plots of upper cylinder pressure versus upper ram displacement were recorded for each treatment and averaged for a measure of the area under the curve. A typical plot is shown in Figure 5.

The total area under the curve AB was measured using a planimeter. The cross-hatched area under CB was also measured and then subtracted from the total to obtain the area of the dotted region, which represents the compression energy. The cross-hatched area represents the amount of energy that would be necessary to extrude a die-full of wafers. However, in an actual process only one wafer is extruded at a time. Therefore the extrusion energy per wafer would only be a small portion of the cross-hatched area. The exact portion is proportional to the length of the wafer, while under compression in the die, divided by the active length of the die (9 inches). The wafer lengths for various moisture contents and extrusion pressures are listed in Table 2 . The effects on wafer length due to back pressure or using a binder are considered to be insignificant.

The compression, extrusion and total energies per wafer were expressed in horsepower-hours which were then divided by the wafer weight to yield specific energy in horsepower-hours per ton. A sample calculation of wafering energy is presented in Appendix A.

5.4.2 Friction.

There were two possible ways of determining the friction associated with any given treatment. One way was to maintain a

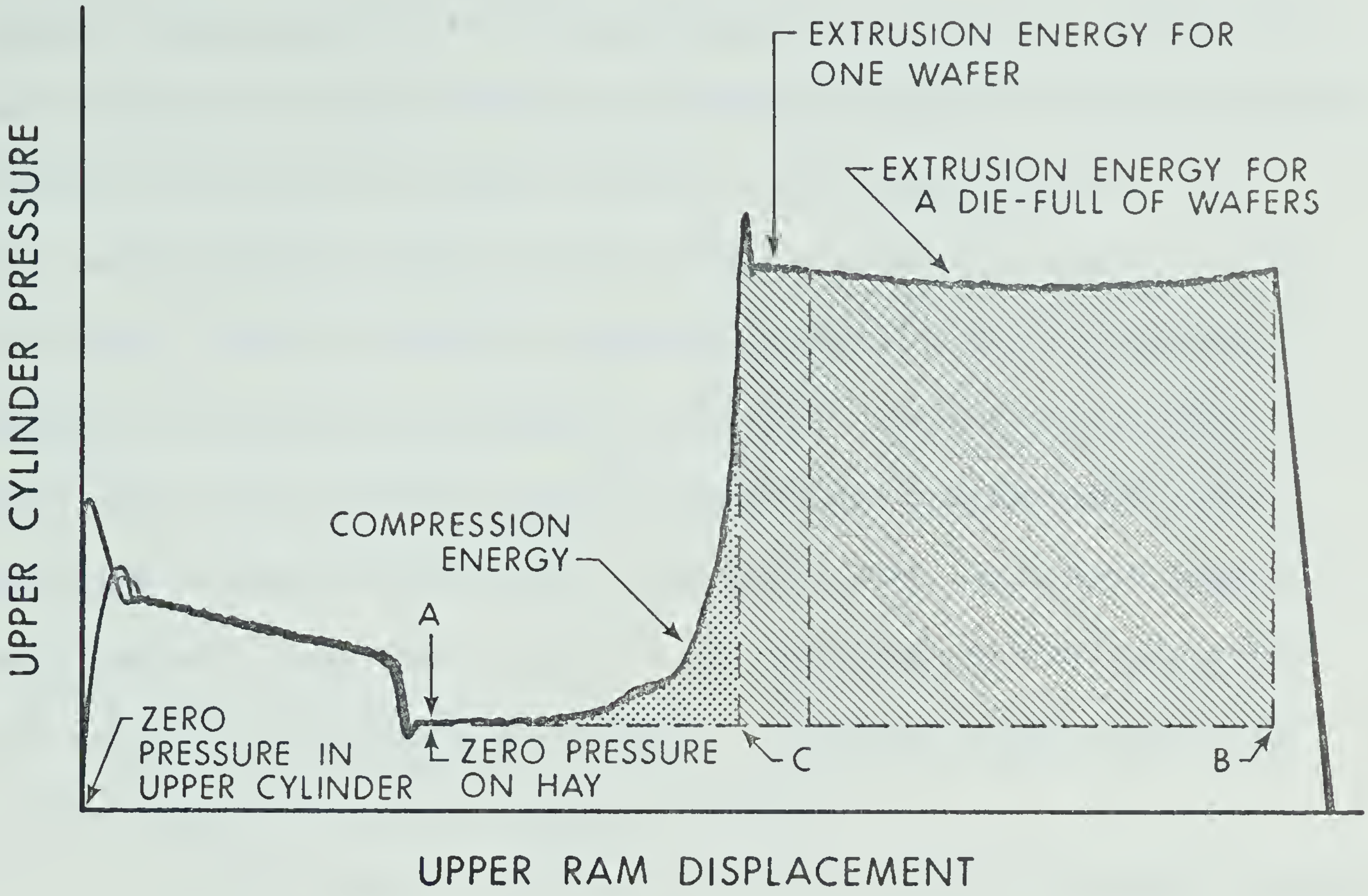

Figure 5: A typical plot of upper cylinder pressure versus upper ram displacement.

TABLE 2: WAFER LENGTHS IN THE DIE.

Extrusion Pressure (psi)	Moisture Content (percent)	Wafer Length (inches)
	10	1.36
1100	20	1.34
	30	1.30
	10	1.05
3400	20	1.13
	30	1.20
	10	.84
5800	20	.93
	30	1.06

constant extrusion time for all combinations of moisture, binder and back pressure and then measure the extrusion pressure (energy) required to force the material through the die at that specified rate. In that case, extrusion time would have been a controlled factor in the experiment, and the extrusion pressure would have been the relative measure of frictional resistance in the die. The other possibility was to hold the extrusion pressure at constant predetermined levels and allow extrusion time to vary. In other words, extrusion pressure would become a controlled factor in the experiment and the extrusion time would be the measure of friction. Longer extrusion times would be associated with higher levels of friction.

In this study, the latter method was used as extrusion pressure could be maintained at a constant level far easier than extrusion time. The extrusion times were obtained by observing the plotter and measuring the time the wafer took to pass through the die. The extrusion time for each treatment was based on an average of at least ten readings.

5.4.3 Wafer Quality.

Ten wafers from each treatment were saved for a durability test. The ten wafers were placed in an air-tight bag and left for approximately twenty-four hours to allow them to fully expand before tumbling. The durability test was carried out and a rating was determined according to the ASAE standard: ASAE S269.1 (2).

The wafer size material which remained after tumbling was returned to the air-tight bag and stored for an indefinite length of time. (This would represent wafers in the centre of a large pile for an extended period of time.) About two months later the wafer

samples for all treatments were checked for mould. Such an observation served as an additional criterion for recommending better wafering practices.

5.4.4 Wafering Efficiency.

A wafering efficiency was calculated for each treatment by dividing the total wafering energy in hp-hr/ton by the wafer durability in percent. This factor helped in choosing which combinations of variables used energy most efficiently.

5.5 Method of Analysis.

Analysis of variance was used to determine if each parameter and their various interactions had an effect. The general form of analysis is shown in Table 3 with two error terms because of the split-plot design (48). It should be noted that the form of analysis for friction (extrusion time), wafer durability and wafering efficiency is slightly different in that the effect of back pressure and its interactions are omitted.

A preliminary analysis was made on each response variable to determine whether error "1" used for testing binders and replicates was significantly different from error "2" used for testing the other sources of variation. If the mean square for error "1" divided by the mean square for error "2" was less than the corresponding tabulated F-ratio at the 10 percent probability level, then the difference between the two errors was not significant. In that case, error "1" (RB) was combined with error "2" to form a pooled error used in testing all sources of variation (5).

Once the significant main effects and interactions had been identified, Duncan's Multiple Range Test (48) was used to establish

exactly which of the treatment levels were significantly different from each other. All multiple range tests were performed at the five percent probability level.

TABLE 3: FORM OF ANALYSIS.

Source of Variance	Degrees of Freedom
Replicates (R)	1
Binder (B)	2
Error "1" RB	2
Moisture Contents (M)	2
MB	4
Extrusion Pressure (U)	2
UB	4
UM	4
UMB	8
Back Pressure (L)	1
LB	2
LM	2
LMB	4
LU	2
LUB	4
LUM	4
LUMB	8
Error "2" All interactions with replicates (R) except RB	51
Total	107

6. RESULTS AND DISCUSSION

6.1 Friction in the Extrusion Die.

6.1.1 Analysis of Variance.

The extrusion times, which served as the measure of friction in the die, are listed in Appendix C for all the possible treatment combinations tested in this experiment. It was observed from this data that all the tests conducted at the low level of back pressure (L_1) had roughly the same extrusion time (approximately 3.3 seconds). In fact a multiple range test indicated that there was no significant difference at the 5 percent probability level, as far as extrusion time was concerned, between any of the 54 treatments containing a low back pressure.

When the back pressure was quite low with respect to the extrusion pressure, the system was very dynamic and variations in frictional resistance in the die had a negligible effect on the rate of extrusion. This suggested that for fast extrusion rates, extrusion time was not a good measure of friction. However, for low extrusion rates, as encountered with a high level of back pressure, the system was slowed down considerably and changes in friction were readily detected from the extrusion time data. So for analyzing variations in friction, only those treatments associated with high levels of back pressure (L_2) were considered.

The analysis of variance for extrusion time is shown in Table 4 without back pressure as a source of variation and with only one error term. (A preliminary analysis indicated that the two error terms could be pooled into one.) All the main effects except

TABLE 4: ANALYSIS OF VARIANCE FOR EXTRUSION TIME.

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	F-Ratio	Probability
R	6.0	1	6.0	0.9	0.3454
B	199.0	2	99.5	15.2	0.0000 ***
M	463.5	2	231.7	35.5	0.0000 ***
U	771.4	2	385.7	59.0	0.0000 ***
MU	458.9	4	114.7	17.6	0.0000 ***
MB	1049.6	4	262.4	40.2	0.0000 ***
UB	205.8	4	51.4	7.9	0.0003 ***
MUB	1013.3	8	126.7	19.4	0.0000 ***
Error	169.9	26	6.5		

*** Significant at the 0.1 % probability level

replicates and all the interactions proved to be significant at the 0.1 percent probability level.

6.1.2 Main Effects.

The general relationship between extrusion pressure and extrusion time or frictional resistance in the die is displayed in Table 5. The increase in friction with higher levels of pressure is partially due to the increase in normal force between the wafer and the die. However, a larger contributor is the tacky substances associated with the alfalfa plant and/or the binder. These substances ooze to the wafer-die interface in increasing amounts as the pressure increases, making the movement of the wafer through the die more difficult.

The juices extracted from the alfalfa plant and/or the binder are only tacky, however, at the lower moisture contents as shown in Table 5. When the moisture content in the hay reaches 30 percent, the lubricating effect of the water prevails and the extrusion time remains at a minimum.

The means of extrusion time for the three levels of binder listed in Table 5 reveal a significant increase in friction when binders are added to the alfalfa hay. These means also indicate that Orzan is significantly stickier than Bentonite. Comparing the feel of these two binders by hand, either in the powder or liquid state would suggest the same.

6.1.3 Moisture Content and Binder Interaction.

The most significant interaction occurs between moisture contents and binders (Figure 6). This interaction can be explained, once again, by the tackiness of the juices present in the material being wafered.

TABLE 5: MEAN EXTRUSION TIMES FOR VARIOUS LEVELS OF THE MAIN EFFECTS.

Main Effects	Levels	Mean Extrusion Time (seconds)
Extrusion Pressure	1100 psi	6.3
	3400 psi	8.3
	5800 psi	15.1
Moisture Content	10 %	12.6[a]
	20 %	11.3[a]
	30 %	5.8
Binder	none	7.5
	Orzan	12.1
	Bentonite	10.1

[a] For a given main effect, means with a common letter in the superscript are not significantly different at the 5 percent probability level.

When alfalfa is wafered without a binder, moisture contents around 20 percent appear to cause the most friction in the die. Wafer machine operators experienced the highest levels of friction at moisture contents as low as 15 percent (28). A more detailed study of friction as affected by moisture content would establish the exact location of the peak frictional resistance of the hay. However, it would suffice noting that in order to minimize friction the moisture content should be extremely low (10 percent) or quite high (30 percent).

The addition of a binder (plus the small amount of water

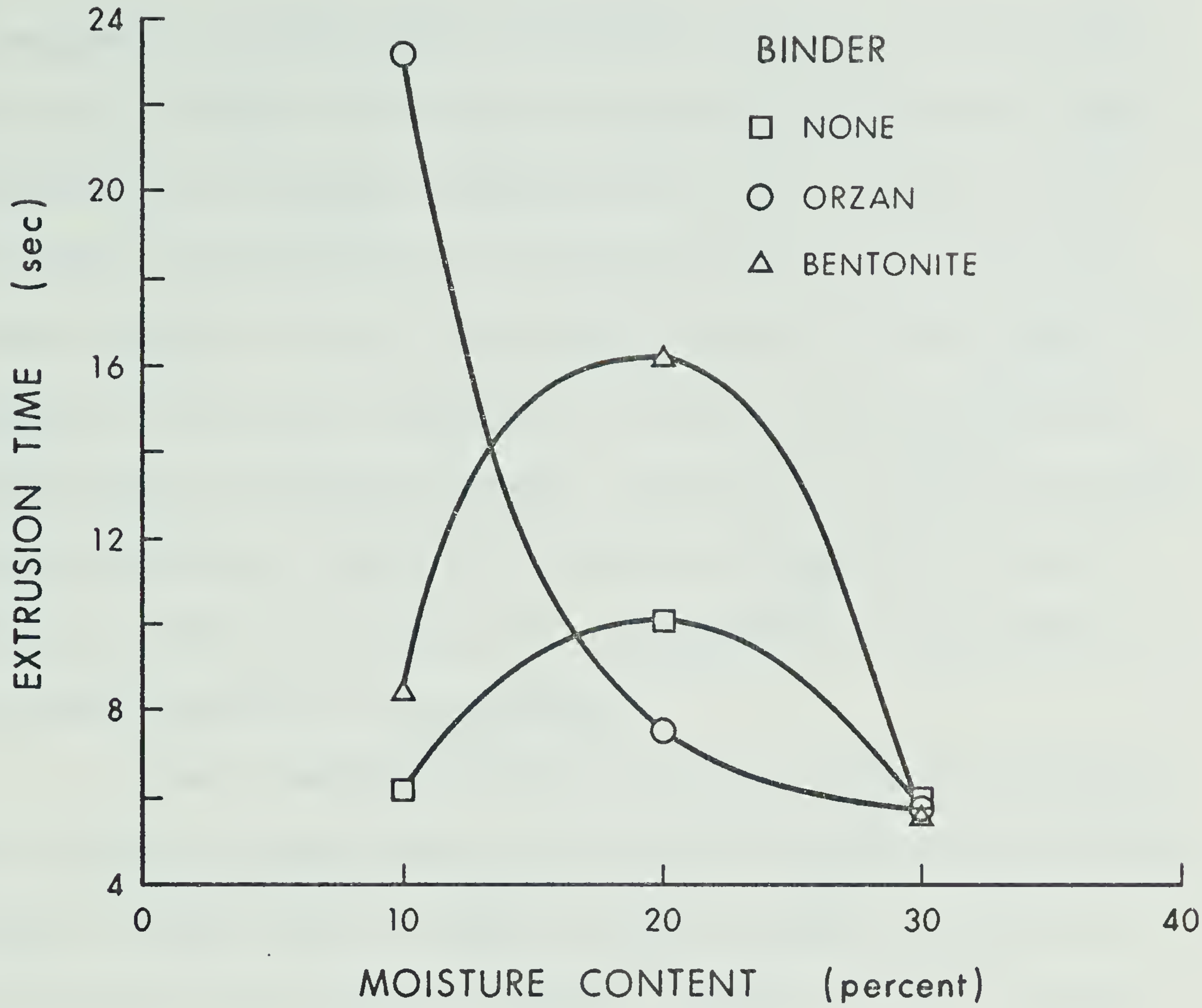

Figure 6: Effect of alfalfa moisture content on extrusion time for various binders.

for activating the binder) alters the effect of moisture on friction (Figure 6). Much of the difference between the two binders with respect to friction is attributed to their properties as bonding agents. Bentonite behaves very much like cement and at no time does it become tacky, so most of the increase in friction with the addition of Bentonite is due to the application of surface moisture for activating the powder. Extra surface moisture on hay of low moisture content (less than 30 percent) tends to add to the frictional resistance in the die more than an equivalent increase in internal moisture. Surface moisture has been added in the wafering process

to improve the binding ability of natural adhesives in the alfalfa plant (23). However, no concern has been expressed for the large increases in die friction associated with such a practice. The much slower extrusion rate at 20 percent moisture compared to 10 percent moisture is due to the relative amounts of free surface moisture at the time of wafering. The hay at 10 percent moisture together with the Bentonite powder, absorb much of the free moisture prior to wafering. However, the absorbing ability at 20 percent moisture is much less leaving more free moisture on the surface of the forage particles to aid adhesion.

Orzan, when used in the liquid form, resembles substances like varnish or shellac which get tackier as they dry out. When this binder is added to hay of about 10 percent moisture content much of the water in the binder is absorbed rapidly by the hay leaving an extremely tacky substance which exhibits very high levels of friction in the die. In hay at 20 percent moisture, the liquid Orzan remains in a fluid state like fresh varnish and provides more of a lubricating effect in the die which offsets any increase in natural adhesion caused by the addition of surface moisture.

It should also be noted that the extrusion time for alfalfa wafers at 30 percent moisture is not affected by the addition of either of the binders in this experiment. There is far too much moisture for any of the applied or natural adhesives to reach a tacky consistency.

6.1.4 Moisture Content and Extrusion Pressure Interaction.

The interaction between moisture content and extrusion pressure is displayed in Figure 7. The trend for increased extrusion

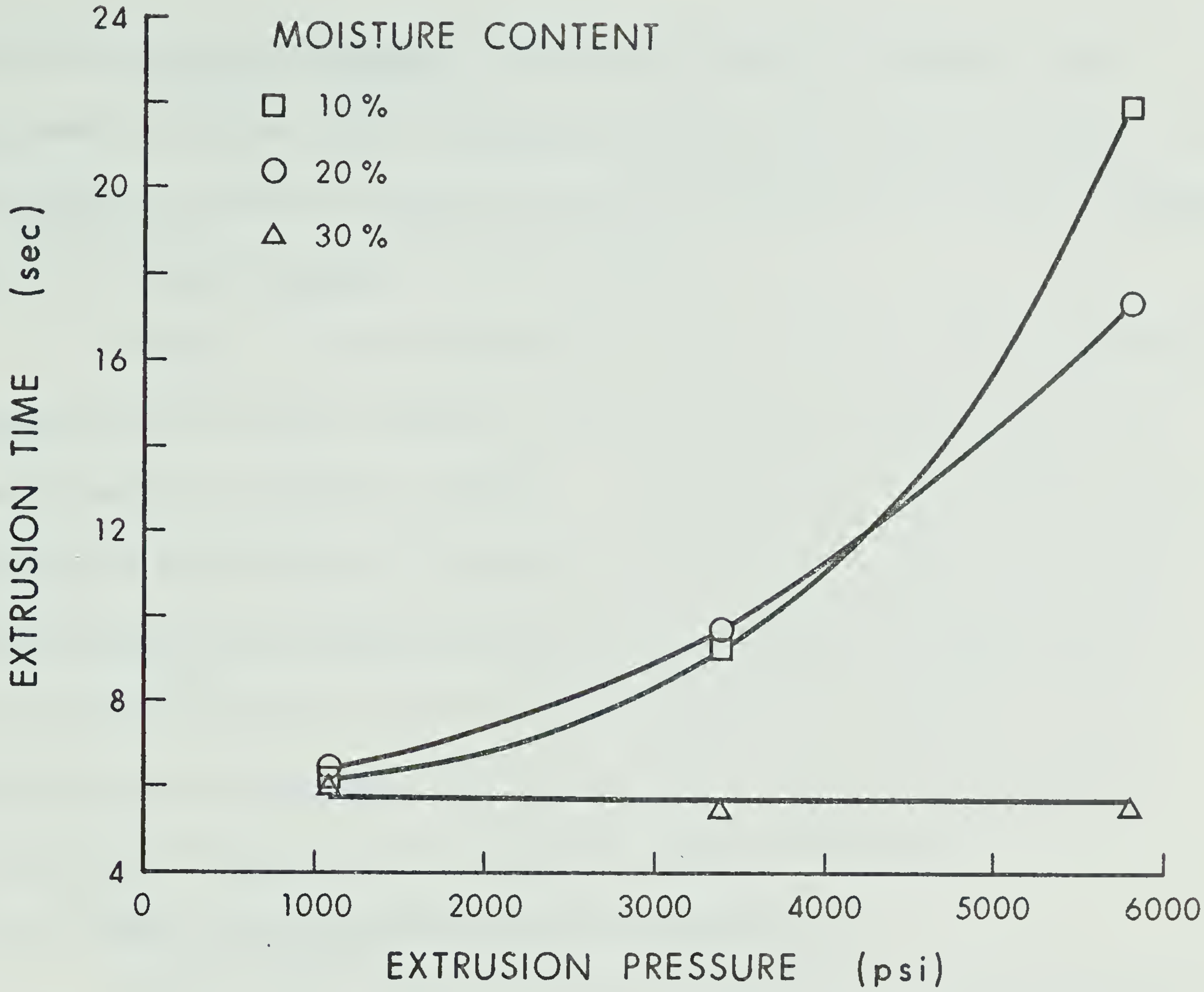

Figure 7: Effect of extrusion pressure on extrusion time for various moisture contents.

times with increased pressures only at the lower two levels of moisture content has been discussed earlier under the main effects. (The divergence of the 10 and 20 percent moisture curves at the upper level of extrusion pressure is due to a large contribution to the mean extrusion time made by the addition of Orzan to hay at 10 percent moisture.)

The lack of variation in extrusion time for different levels of extrusion pressure, demonstrated by the hay at 30 percent moisture (Figure 7), is explained by the excessive amount of water in the hay, making the existence of a sticky wafer-die interface virtually impossible. No matter how much pressure is applied to a wafer at

30 percent moisture content, the friction remains unchanged. Any increases in normal force between the wafer and die due to higher pressures are offset by extra lubrication in the die from the increased amounts of water squeezed out of the hay.

Figure 7 also indicates that there is very little difference between the extrusion times for the three levels of moisture at the lowest level of extrusion pressure. Pressures as low as 1100 psi are apparently insufficient in forcing the glutinous fluids to the outer edges of the wafer where the frictional resistance of these fluids can be felt in the die. An extrusion pressure of 1100 psi would be desirable for minimizing friction and energy requirements, provided a satisfactory wafer can be produced at this energy level.

6.1.5 Binder and Extrusion Pressure Interaction.

Table 6 shows the interaction between binders and extrusion pressure. Very few noticeable trends in these means were found to be significant. However, those extrusion times which are distinctly longer than the rest occur at the highest extrusion pressure and with the application of binders. The reason for this has been described under the main effects.

6.1.6 Other Sources of Variation in Friction.

All the important effects on friction have been discussed under the main effects and the two-factor interactions. A discussion of the three-factor interaction for moisture content, extrusion pressure and binder would not contribute any pertinent information, and therefore, is omitted.

Although die temperature was not an intentional source of variation for die friction, its effect was quite noticeable as wafers

TABLE 6: MEAN EXTRUSION TIME (SEC) AS AFFECTED BY BINDERS AND EXTRUSION PRESSURE.

Binders \ Pressure	1100 psi	3400 psi	5800 psi
None	5.9^{a}	$7.5^{a,b}$	$8.9^{a,b}$
Orzan	$6.9^{a,b}$	9.4^{b}	20.2
Bentonite	$6.1^{a,b}$	$7.9^{a,b}$	16.3

[a,b] Means with a common letter in the superscript are not significantly different at the 5 percent probability level. This applies to rows and columns.

passed through different temperature zones in the die. The ends of the die were somewhat cooler than the middle section due to the location of the heating elements. The wafers took longer to pass through these narrow bands at either end of the die than they took to pass through the larger heated section. From this it is concluded that, in general, friction is inversely proportional to die temperature.

Meaningful results for all sources of variation were obtained by using extrusion time as the relative measure of die friction, provided the extrusion rate was fairly slow. However, the conclusions from this experiment pertaining to friction should apply equally well to any extrusion rate.

6.2 Energy Requirements for Wafering Alfalfa.

6.2.1 Analysis of Variance.

The wafering energy was analyzed in terms of compression energy, extrusion energy and the total of these two portions. When the compression and extrusion energies were considered separately, the effect of the split-plot was found to be significant and therefore

the two error terms had to be used in each case. However, in analyzing the total of the two energies, the two error terms showed no significant difference and were therefore pooled into one.

Wafering energy was not intended to vary with changes in die friction. Extrusion pressure was a controlled variable and did not fluctuate very much from a given setting, therefore the variations in wafering energy were primarily a function of the pressure setting, the wafer size under compression in the die and the wafer weight (Appendix A). Had extrusion pressure been a dependent variable instead of extrusion time, the die friction and the corresponding wafering energy would have been represented by the same measurement (area under the curve), and could have been analyzed simultaneously.

6.2.2 Compression Energy.

The main effects on compression energy, which were found to be significant in Table 7, include replicates, moisture content and extrusion pressure. The effect due to replicates however, was caused by an error in the equipment and not by differences between the two lots of alfalfa. The error was only noticeable over a long period of time and showed no detrimental effect within a replicate.

The main effect of extrusion pressure is presented in Table 8. In general, the higher peaks on the pressure-displacement curves, corresponding to higher extrusion pressures, mean larger compression energies (Figure 5).

The rate at which the peak pressure is reached, explains part of the moisture effect on compression energy. Moisture in the hay provides a lubricant which facilitates the movement of forage particles in the compaction process. The higher the moisture content,

TABLE 7: ANALYSIS OF VARIANCE FOR COMPRESSION ENERGY.

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	F-Ratio	Probability
R	30.0	1	30.0	18.7	0.0496 *
B	1.8	2	0.9	0.6	0.6398
Error "1" BR	3.214	2	1.607		
M	58.6	2	29.3	50.8	0.0000 ***
L	1.9	1	1.9	3.2	0.0789
U	63.5	2	31.8	55.1	0.0000 ***
ML	0.6	2	0.3	0.5	0.5946
MU	25.4	4	6.3	11.0	0.0000 ***
MB	2.6	4	0.6	1.1	0.3598
LU	0.3	2	0.1	0.2	0.7911
LB	0.7	2	0.3	0.6	0.5543
UB	1.4	4	0.3	0.6	0.6737
MLU	1.6	4	0.4	0.7	0.5999
MLB	2.5	4	0.6	1.1	0.3642
MUB	3.0	8	0.4	0.7	0.7267
LUB	0.7	4	0.2	0.3	0.8866
MLUB	2.5	8	0.3	0.5	0.8196
Error "2"	29.410	51	0.577		

* Significant at the 5 % probability level

*** Significant at the 0.1 % probability level

TABLE 8: MEAN COMPRESSION ENERGY FOR VARIOUS LEVELS OF THE MAIN EFFECTS.

Main Effects	Levels	Mean Compression Energy (hp-hr/ton)
Extrusion Pressure	1100 psi	2.14
	3400 psi	3.40
	5800 psi	3.97
Moisture Content	10 %	4.06
	20 %	3.18
	30 %	2.26

the faster these particles move together; thus reducing the compression area under the curve and the energy associated with that area.

The other part of the moisture effect on compression energy applies to extrusion and total energies as well. In the final calculation of specific energy in horsepower-hours per ton, the wafer weight that is used varies with moisture content. The wafers of higher moisture weigh more and therefore require less energy on a per ton basis. Table 8 shows the total moisture effect on compression energy.

Figure 8 shows the effect of the moisture-pressure interaction on compression energy. The general shape of all three curves suggests that the increments in compression energy get smaller as the applied pressure increases. Once the maximum density for a given moisture content has been reached, any additional pressure will be received with no further travel in the ram and will therefore add nothing to the compression energy.

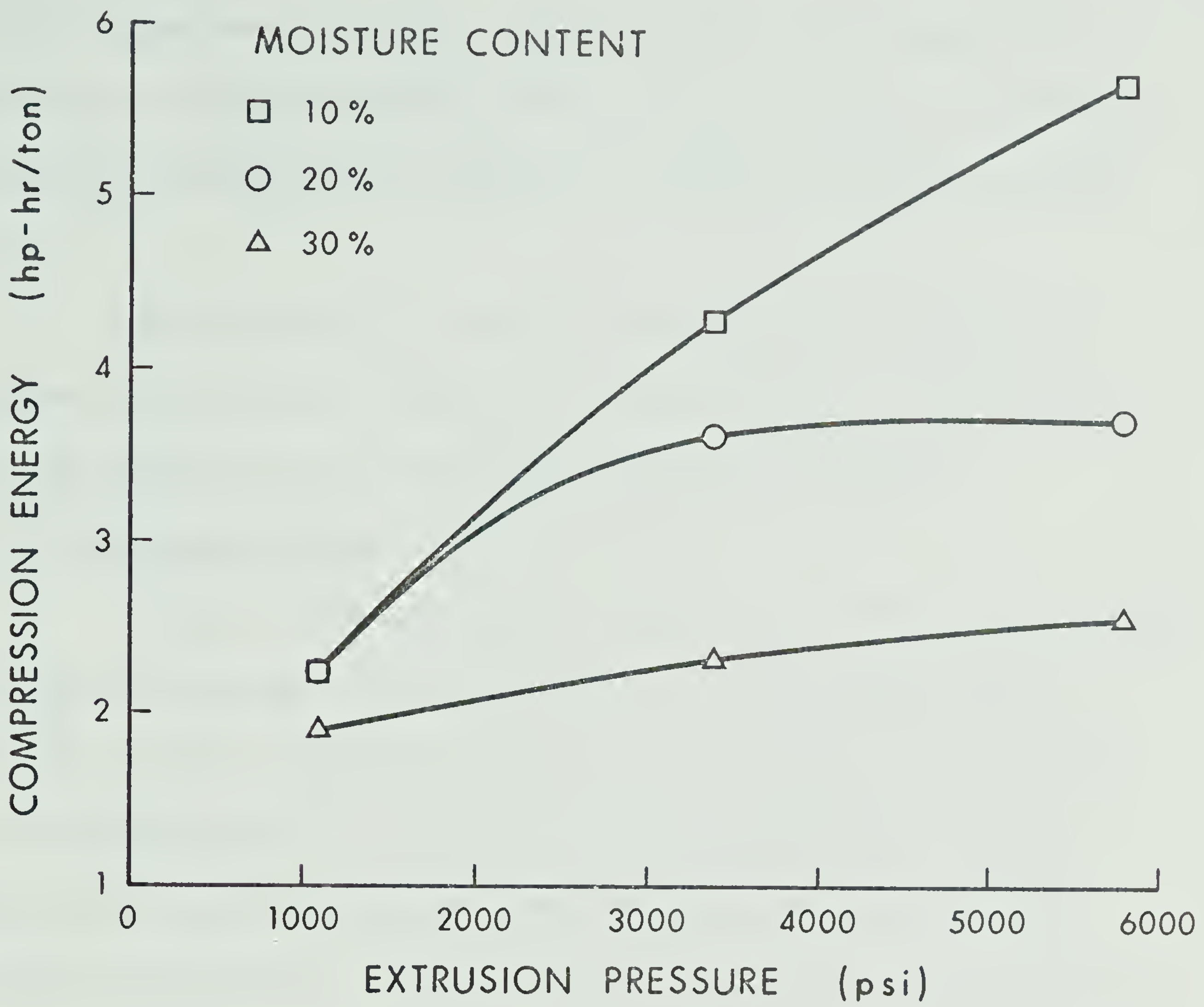

Figure 8: Effect of extrusion pressure on compression energy for various moisture contents.

Alfalfa at 10 percent moisture is very dry and difficult to compact. Extremely high pressures, in excess of 6000 psi, are required to achieve a maximum density with hay in this dry state. As moisture content and its lubricating effect increases, compaction becomes easier as displayed by the hay at 20 percent moisture. However if the moisture content is too high, the water, being incompressible, interferes with a thorough compaction of the hay and limits the maximum density no matter how much additional pressure is applied. This is indicated by the curve for 30 percent moisture, where the increase in compression energy over the range of pressures

in this experiment is small, suggesting that the maximum wafer density is attained with very little compression and that higher pressures contribute very little to a further reduction in wafer size.

The interaction discussed above can be summarized as follows: The pressure required to attain maximum compression of the hay decreases as the moisture content is increased.

6.2.3 Extrusion Energy.

Table 9 indicates several significant effects with respect to extrusion energy. The effects due to back pressure and its interaction with extrusion pressure are extremely small compared to the main effects of extrusion pressure and moisture content. The effects of back pressure simply reveal minute fluctuations in extrusion pressure caused by friction effects. Since friction was dealt with separately and was not intended to play a part in the energy analysis, its effects require no further discussion.

The effects of moisture content and extrusion pressure shown in Figure 9 are of major concern regarding extrusion energy. The general tendency exhibited at all three moisture contents is for extrusion energy to increase at a decreasing rate as extrusion pressure increases. Since the extrusion pressure is actually the average height of the pressure-displacement curve used in measuring extrusion energy, the extrusion energy is expected to be closely related to this applied pressure. However the reason for a non-linear relationship is explained by the fraction of the total area under the curve (Figure 5) used in obtaining the extrusion energy on a per wafer basis. This fraction is proportional to the length

TABLE 9: ANALYSIS OF VARIANCE FOR EXTRUSION ENERGY.

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	F-Ratio	Probability
R	0.6	1	0.6	7.6	0.1100
B	0.4	2	0.2	2.3	0.2994
Error "1" BR	0.167	2	0.083		
M	13.6	2	6.8	196.7	0.0000 ***
L	1.1	1	1.1	31.7	0.0000 ***
U	1062.9	2	532.5	15420.9	0.0000 ***
ML	0.0	2	0.0	0.2	0.8267
MU	1.6	4	0.4	11.3	0.0000 ***
MB	0.2	4	0.1	1.5	0.2284
LU	1.7	2	0.9	24.3	0.0000 ***
LB	0.0	2	0.0	0.2	0.7801
UB	0.0	4	0.0	0.7	0.5994
MLU	0.1	4	0.0	0.9	0.4936
MLB	0.1	4	0.0	0.9	0.4976
MUB	0.2	8	0.0	0.7	0.7220
LUB	0.0	4	0.0	0.5	0.7398
MLUB	0.1	8	0.0	0.4	0.8885
Error "2"	1.758	51	0.034		

*** Significant at the 0.1 % probability level

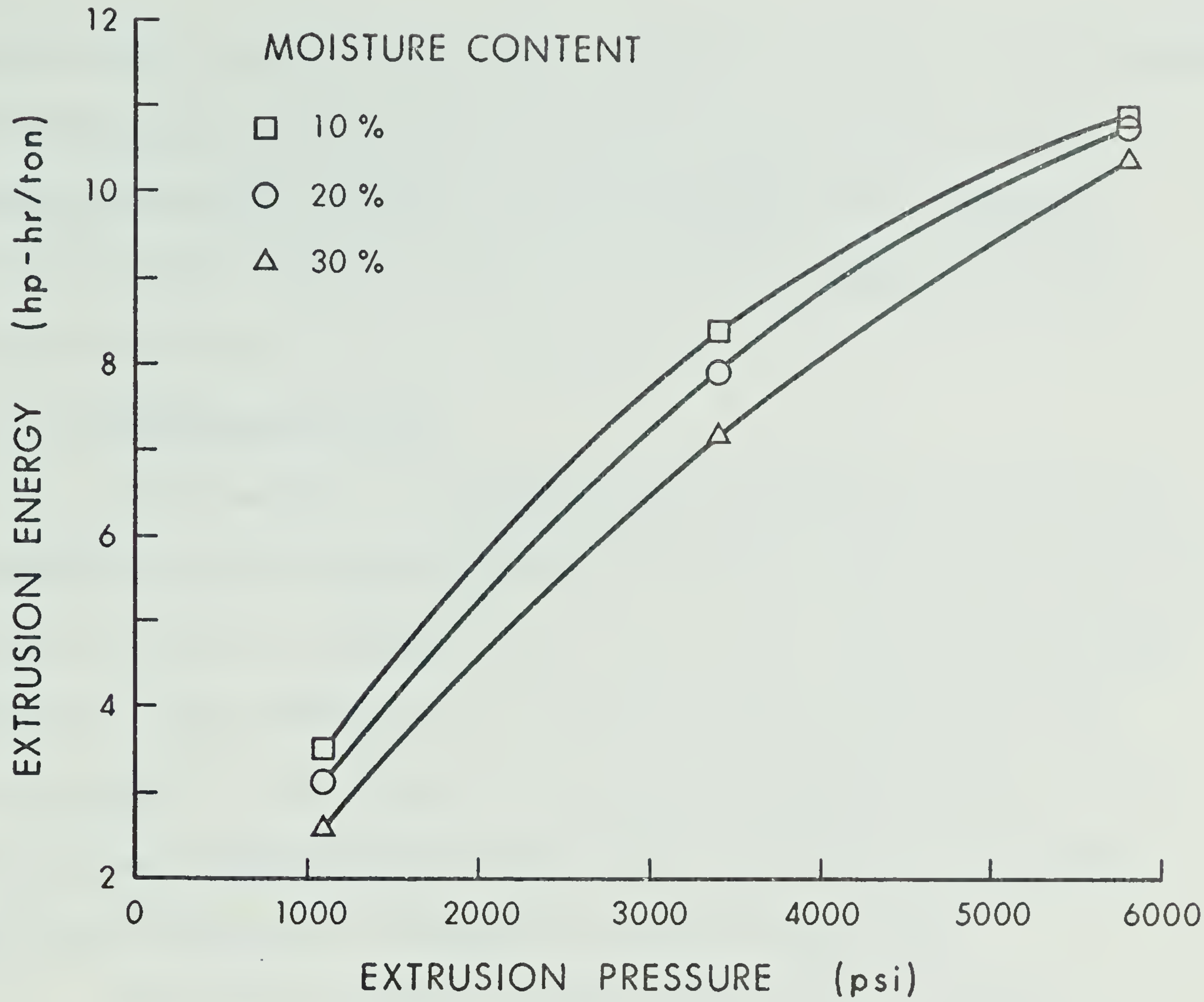

Figure 9: Effect of extrusion pressure on extrusion energy for various moisture contents.

of the wafer while it is in the die (Appendix A); and the wafer lengths as listed in Table 2 are a non-linear function of extrusion pressure.

The effect on extrusion energy caused by moisture content is partially related to wafer length as well. Higher moisture levels in the hay produce wafers that are less dense and longer than those produced from dry hay. So the extrusion energy per wafer of damp hay would be based on a larger portion of the area under the curve than the extrusion energy per wafer of dry hay. Increased extrusion energy with increased moisture would indeed be the trend if the energy was calculated on a per wafer basis. However, the normal

practice is to determine the energy required to produce a ton of wafers. By dividing each energy value by the wafer weight in tons, the tendency for greater specific extrusion energies with decreased moisture content (lighter wafers) overrides the above and becomes the dominant trend as shown in Figure 9.

6.2.4 Total Wafering Energy.

This section is intended simply to bring the two portions of wafering energy together and show that most of the effects observed in the previous two sections carry over to the total wafering energy (Table 10). The effects due to replicates and back pressure are of no interest to the analysis of energy as mentioned before. The moisture and pressure effects share some of the same explanations that were presented for compression and extrusion energy.

The graphs of total wafering energy versus extrusion pressure for varying levels of moisture content (Figure 10) closely resemble those for extrusion energy, as extrusion energy makes up the largest portion of the total. The noticeable interaction is primarily due to the contributions from compression energy.

6.3 Wafer Quality.

Wafer quality, in terms of a durability rating and the occurrence of mould, was determined for each test to provide a means of qualifying any recommendations which might come out of this study to improve the wafering process. Wafer durability as affected by the various independent variables in this experiment was analysed to discover the basic trends in the data. These trends were found to agree quite well with those established by previous researchers

TABLE 10: ANALYSIS OF VARIANCE FOR TOTAL WAFERING ENERGY.

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	F-Ratio	Probability
R	39.4	1	39.4	63.3	0.0000 ***
B	3.2	2	1.6	2.6	0.0856
M	127.9	2	64.0	102.8	0.0000 ***
L	5.8	1	5.8	9.3	0.0036 **
U	1644.6	2	822.3	1321.3	0.0000 ***
ML	0.6	2	0.3	0.5	0.6040
MU	21.9	4	5.5	8.8	0.0000 ***
MB	3.0	4	0.7	1.2	0.3217
LU	2.1	2	1.1	1.7	0.1949
LB	0.6	2	0.3	0.5	0.6038
UB	1.3	4	0.3	0.5	0.7318
MLU	1.0	4	0.3	0.4	0.8049
MLB	2.3	4	0.6	0.9	0.4594
MUB	3.3	8	0.4	0.7	0.7279
LUB	0.8	4	0.2	0.3	0.8701
MLUB	3.2	8	0.4	0.6	0.7424
Error	32.985	53	0.622		

** Significant at the 1 % probability level

*** Significant at the 0.1 % probability level

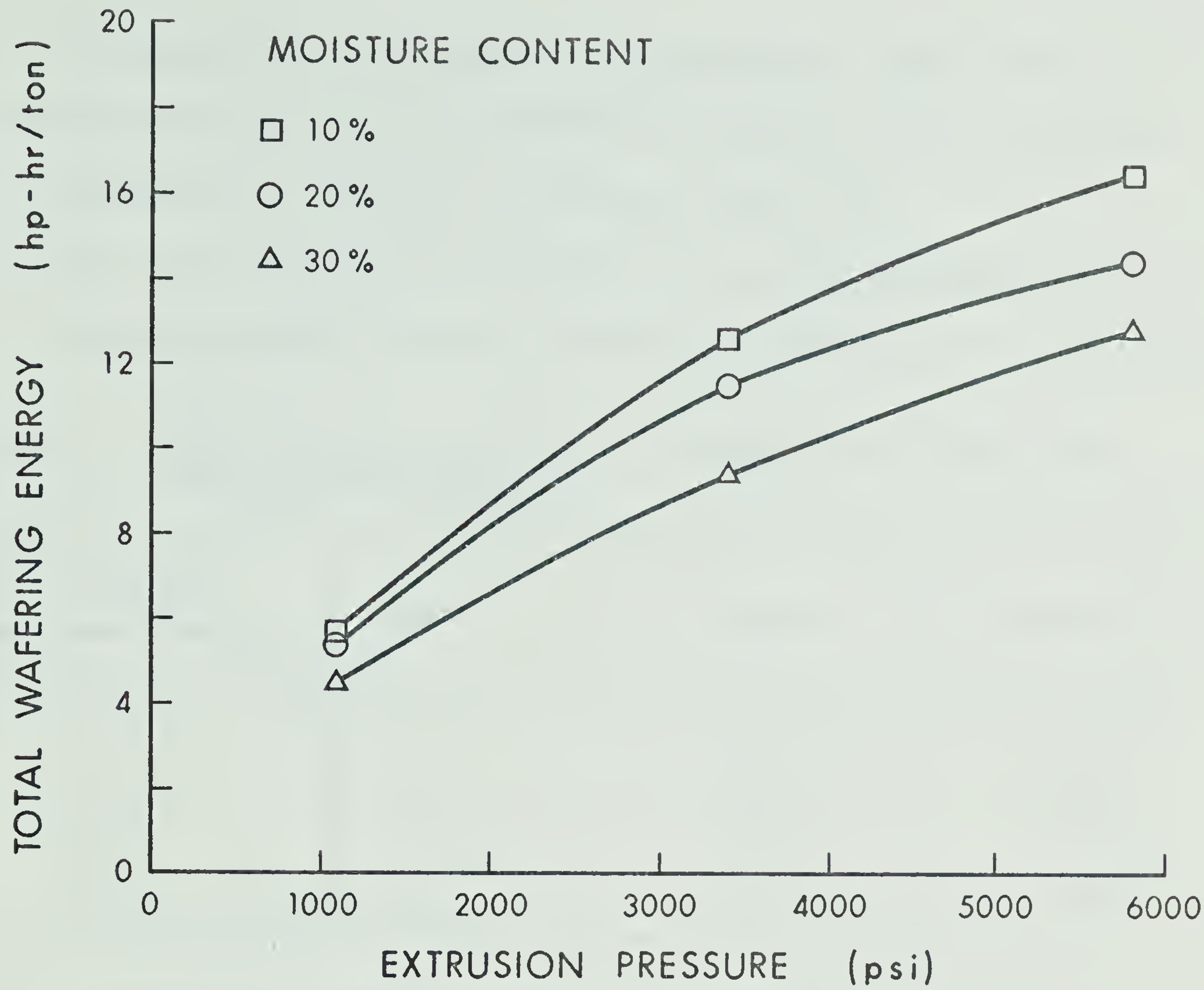

Figure 10: Effect of extrusion pressure on total wafering energy for various moisture contents.

in this area, and therefore a detailed discussion is not warranted. (An analysis of variance of the durability is shown in Appendix D.)

However some isolated characteristics in the data will be mentioned at this time as they will be of assistance in establishing feasible operating conditions for the wafering process.

1. When no binder is applied to the alfalfa hay, a moisture content of 20 percent yields a much more durable wafer than can be produced with hay at 10 or 30 percent moisture (Table 11).
2. The addition of a liquid binder only results in significant durability improvements for hay at 10 percent moisture (Table 11).
3. As far as durability is concerned there is no significant

difference between using Orzan or Bentonite (Table 11).

4. There is no change in durability by increasing the extrusion pressure from 3400 psi to 5800 psi (Table 12).

5. Hay at 20 percent moisture shows no significant change in durability over all three levels of extrusion pressure (Table 12).

TABLE 11: MEAN DURABILITY RATING (%) AS AFFECTED BY BINDER LEVEL AND MOISTURE CONTENT.

Moisture \ Binder	None	Orzan	Bentonite
10 %	76.5^{c}	96.6^{a}	$89.9^{a,b}$
20 %	97.4^{a}	98.4^{a}	98.3^{a}
30 %	$83.7^{b,c}$	86.0^{b}	$89.2^{a,b}$

a,b,c Means with a common letter in the superscript are not significantly different at the 5 percent probability level. This applies to rows and columns.

TABLE 12: MEAN DURABILITY RATING (%) AS AFFECTED BY EXTRUSION PRESSURE AND MOISTURE CONTENT.

Moisture \ Pressure	1100 psi	3400 psi	5800 psi
10 %	68.5	$96.4^{a,b}$	$98.1^{a,b}$
20 %	$96.6^{a,b}$	98.9^{a}	98.7^{a}
30 %	79.7	$89.8^{a,b}$	89.4^{b}

a,b Means with a common letter in the superscript are not significantly different at the 5 percent probability level. This applies to rows and columns.

Figures 11 and 12 display the relative appearance of wafers formed at different parameter levels. The first figure shows the improvement in durability with longer extrusion times and higher pressures. The second figure indicates the effect on wafer formation when binders are added and when moisture content is varied.

The occurrence of mould at various moisture levels was analyzed by visual observation. After two months in air-tight storage at room temperature, wafers at 10 percent moisture showed no sign of mould, wafers at 20 percent moisture had traces of mould on some samples and wafers at 30 percent moisture were completely covered in mould. It is felt that if wafers at 20 percent moisture were left to air dry for several hours before being placed in a bin, they could be stored with the same safety as wafers at 10 percent moisture.

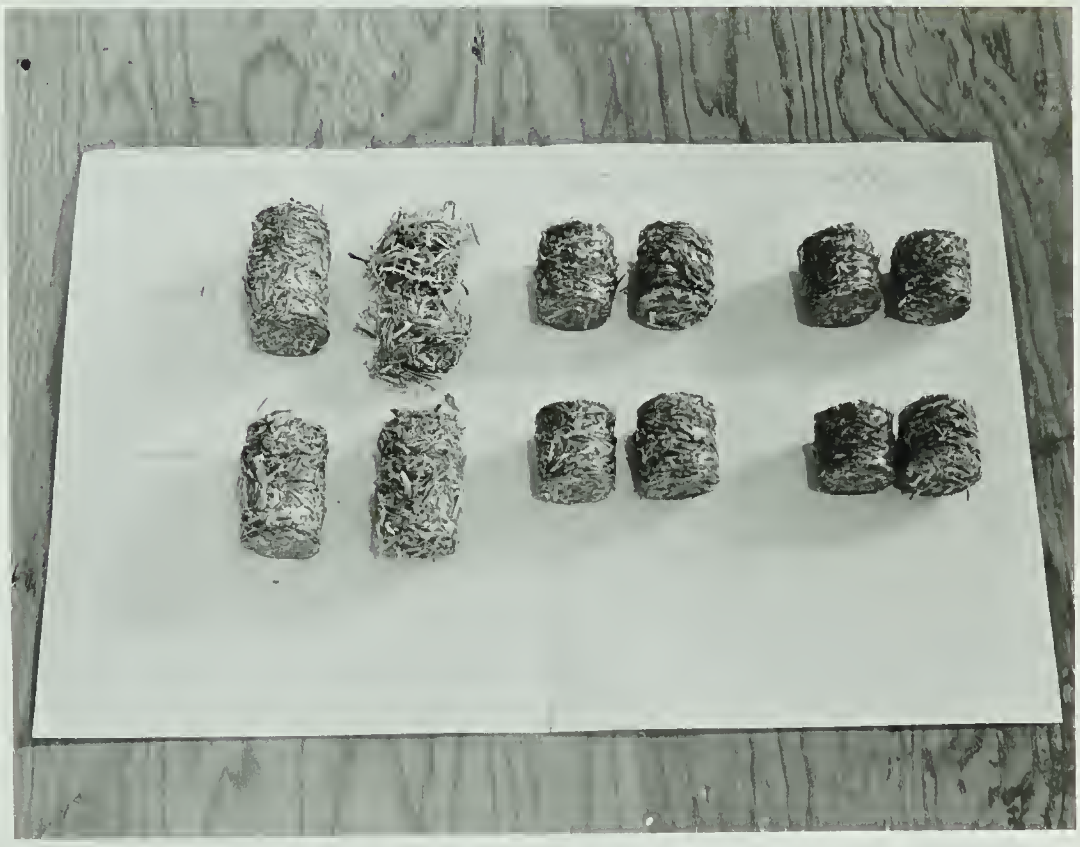

Figure 11: The relative appearance of wafers before (on the left in each pair) and after (on the right in each pair) the durability test for three levels of extrusion pressure and two levels of extrusion time. (Wafers were formed at 10 percent moisture without a binder.)

Figure 12: The relative appearance of wafers before (on the left in each pair) and after (on the right in each pair) the durability test for three levels of moisture content (top) and three levels of binder (bottom). (The wafers with varying moisture contents were formed without a binder, at 3400 psi and 3.5 seconds extrusion time. The wafers with varying binder levels were formed with 10 percent moisture, at 1100 psi and 7 seconds extrusion time.)

6.4 Establishing Optimum Wafering Conditions.

At this point all the information on die friction, energy requirements and wafer quality is brought together to establish some optimum operating conditions for the wafering process. However it should be recognized that the following optimization applies specifically to the extrusion press used in this experiment. The

differences between this single-shot wafering press and the full-scale machine are far too great to make any direct correlations between the two. An optimization of wafering conditions for the commercial process, though, might follow the same pattern as set down in this section.

Since the extrusion stage of the process is the most wasteful in terms of energy, the fraction of the total energy consumed by extrusion was determined for all tests and analyzed. This fraction, like the energy data, was very much affected by extrusion pressure and moisture content as shown in Table 13. According to the means of the extrusion energy to total energy ratios, it would be advisable to restrict the wafering process to hay at 10 percent moisture and any extrusion pressure or the lowest extrusion pressure (1100 psi) and any moisture content. These conditions yield the lowest ratios which mean less energy wasted on extrusion.

Further improvements for the extrusion segment of the process can be discovered by referring to the discussions on die friction. The use of binders is feasible provided the extrusion pressure is kept fairly low (less than 3400 psi). If no binder is used, alfalfa at around 20 percent moisture should be avoided at the higher pressures (greater than 3400 psi). Also the addition of surface moisture should not be practised where friction is going to be a problem.

Having reduced extrusion energy to a satisfactory level, the next step is to investigate whether good quality wafers can be produced with this amount of energy. First of all the wafers with moisture contents in excess of 20 percent can be eliminated due to

TABLE 13: RATIO OF EXTRUSION ENERGY TO TOTAL ENERGY AS AFFECTED BY EXTRUSION PRESSURE AND MOISTURE CONTENT.

Moisture \ Pressure	1100 psi	3400 psi	5800 psi
10 %	.61[a]	.67[b]	.66[b]
20 %	.59[a]	.69[b]	.75[c]
30 %	.59[a]	.76[c]	.81

[a,b,c] Means with a common letter in the superscript are not significantly different at the 5 percent probability level. This applies to rows and columns.

their lack of preservation in storage. To aid in eliminating other treatment levels the wafering efficiency will be used in conjunction with wafer quality. The wafering efficiency, obtained by dividing the total wafering energy for a test by the corresponding wafer durability rating, indicates how efficiently the energy input is utilized in increasing wafer durability. The smaller ratio implies a more efficient process.

An analysis of variance was carried out to determine if there was any significant difference between the wafering efficiencies for various treatments (Table 14). To exclude the effect of extrusion time on the durability used in calculating efficiency, only the data for low back pressure (fairly constant extrusion times) were used in this analysis. Only moisture content and extrusion pressure had any effect on wafering efficiency. This is because the total wafering energy is the major contributor to variations in the efficiency data; and the total wafering energy is greatly affected by moisture and pressure as seen before. Most of the durability ratings are

TABLE 14: ANALYSIS OF VARIANCE FOR WAFERING EFFICIENCY (INCREASED BY A FACTOR OF 10).

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	F-Ratio	Probability
R	0.0	1	0.0	0.38	0.5414
B	0.2	2	0.1	1.97	0.1599
M	1.1	2	0.5	8.75	0.0012 **
U	6.0	2	3.0	49.36	0.0000 ***
MU	0.2	4	0.1	0.97	0.4407
MB	0.5	4	0.1	2.15	0.1028
UB	0.3	4	0.1	1.27	0.3088
MUB	0.7	8	0.1	1.46	0.2199
Error	1.577	26	0.061		

** Significant at the 1 % probability level

*** Significant at the 0.1 % probability level

clustered within a short range thus contributing hardly any variation to the efficiency data.

On the whole, wafering efficiency improves with reductions in extrusion pressure and increases in moisture content. Table 15 displays this trend over limited ranges of pressure and moisture. The highest level of extrusion pressure was disregarded as it caused large increases in wafering energy, but made little or no improvements in wafer durability. The binder effects were included with the 10 percent moisture content to demonstrate that wafers at this moisture level could be formed efficiently with an extrusion pressure of 1100 psi, provided a binder like Orzan is added to the hay.

Of the feasible treatments associated with the lower two extrusion pressures, the lower two moisture contents and the three levels of binders, all but two of them produce wafers with a durability rating greater than 90 percent (Figure 13). However all these high quality wafers are not produced with the same efficiency. Referring to Table 15, the treatments with the best efficiency which would yield the most desirable wafering process include:

1. extrusion pressure, 1100 psi
   back pressure in the die, low (350 psi)
   moisture content, 20 percent
   binder, none
2. extrusion pressure, 1100 psi
   back pressure in the die, low (350 psi)
   moisture content, 10 percent
   binder, Orzan

Obviously, in a real situation, the first process would be the least

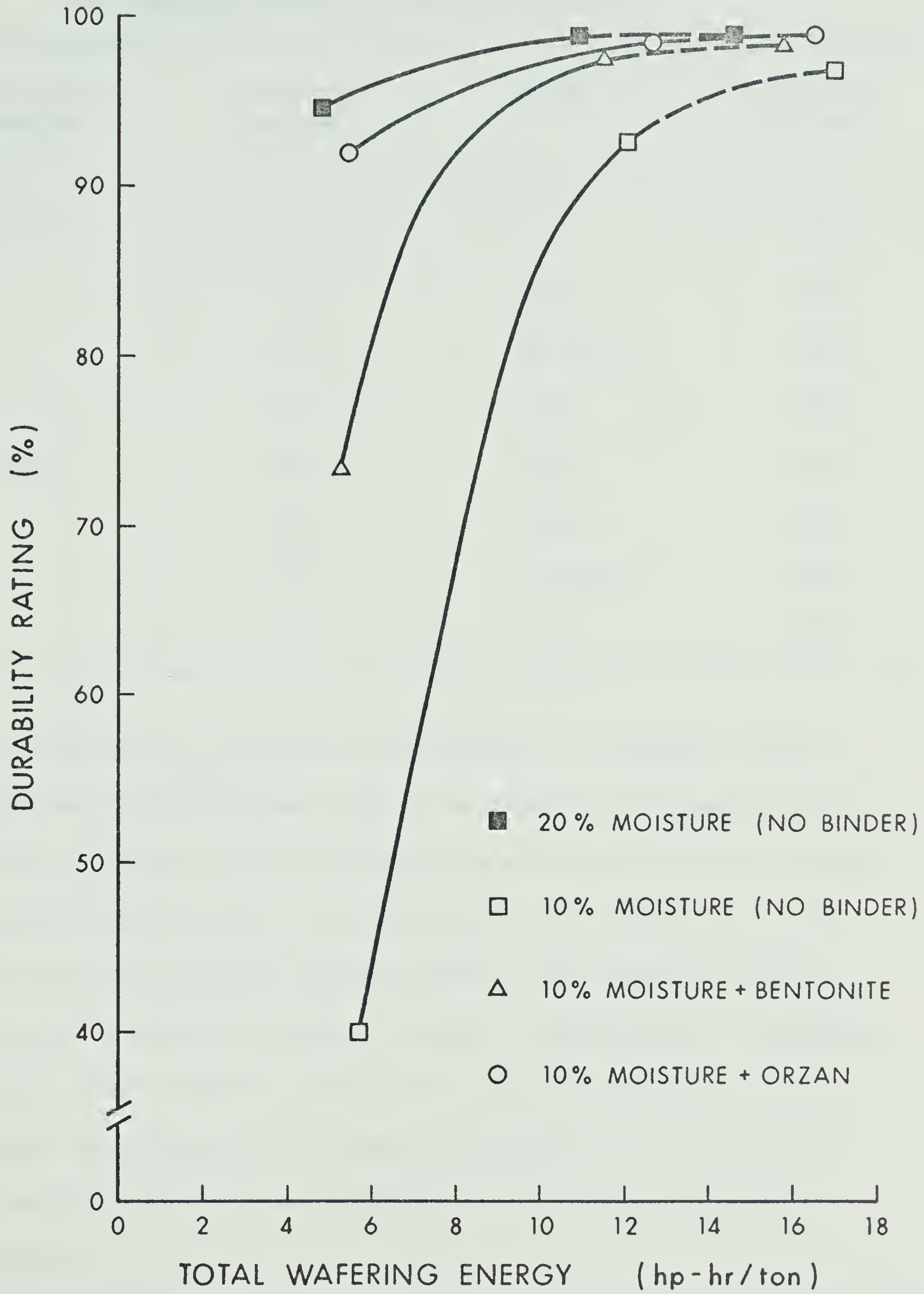

Figure 13: Durability rating related to total wafering energy as affected by moisture content and binders.

TABLE 15: WAFERING EFFICIENCY (HP-HR/TON PER % OF DURABILITY) FOR SEVERAL FEASIBLE WAFERING CONDITIONS.

Extrusion Pressure (psi)	Moisture Content (percent)	Binder	Wafering Efficiency
1100	10	none	.1775
	10	Orzan	.0590
	10	Bentonite	.0730
	20	none	.0515
3400	10	none	.1300
	10	Orzan	.1285
	10	Bentonite	.1185
	20	none	.1105

costly of the two. The cost of dehydration, if required, would be slightly less if the hay only had to be dried to 20 percent moisture. The relative saving would be approximately 50 cents per ton of wafers assuming the average cost of natural gas to be 5 cents per ton of hay per percent decrease in moisture (38). The greatest saving, however, is in wafering without a binder. The increase in operating cost when using a binder is about $5.00 per ton of wafers produced when Orzan is applied at 2.5 percent by weight (15) or $1.00 per ton of wafers produced when Bentonite is applied at 1.7 percent by weight (6).

Increasing extrusion pressure from 1100 psi to 3400 psi would cause an increase in energy requirements of approximately 6 horsepower-hours/ton of wafers. With the present cost of industrial

energy averaging 2.5 cents per kilowatt-hour, this increase in extrusion pressure would represent an increase in operating cost of about 11 cents per ton of wafers. Therefore, when the hay is at 10 percent moisture, it would certainly be more economical to wafer at a higher extrusion pressure (3400 psi) rather than adopt the use of a bonding agent (Orzan).

7. SUMMARY AND CONCLUSIONS

The friction associated with the extrusion of alfalfa hay reaches a maximum at high levels of back pressure in the die, and at extrusion pressures of 5800 psi or greater when the hay contains

a) 20 percent moisture and no binder or

b) 10 percent moisture and Orzan or

c) 20 percent moisture and Bentonite.

The maxima attributed to the addition of the two binders is a significant increase over that produced by hay without a binder. At the lowest extrusion pressure (1100 psi) friction is greatly reduced and is independent of moisture content and binders.

In addition to the detrimental affect of die friction on total wafering energy there are also direct contributions made by extrusion pressure and moisture content. The compression energy increases with applied (extrusion) pressure until the maximum wafer density is achieved and then the compression energy remains constant. The pressure required to produce this terminal density, decreases with higher moisture contents. This means more energy is required to thoroughly compress dry hay than is required for damp hay. The extrusion stage of the process consumes a larger portion of the total wafering energy as extrusion pressure and moisture content increases. In order to maintain a good balance between compression and extrusion energy and to eliminate much of the wasteful friction it is necessary to remain at low pressure levels (less than 3400 psi).

At an extrusion pressure of 1100 psi, alfalfa at 10 percent moisture with Orzan added or 20 percent moisture without a binder produce a very durable wafer (durability rating in excess of 90

percent). Operating under these conditions, which consumes approximately 5 horsepower-hours per ton of wafers, produced the optimum wafering efficiency (i.e. the least amount of energy required to achieve very good wafer durability).

In terms of economic efficiency the wafer durability should be improved by increasing extrusion pressure (wafering energy) rather than adding binders.

8. SUGGESTIONS FOR FURTHER RESEARCH

1. The conclusions reached in this study cannot be transferred directly to the commercial wafering machines. Tests, using similar variables, should be conducted on an industrial-scale machine to verify what has been revealed in this simulative experiment pertaining to friction and energy requirements in extruding hay.
2. The application of binders to permit wafering alfalfa with less energy is limited due to cost. This experiment should be extended to include other binders and other binder concentrations. The purpose would be to produce good wafer quality with a minimum of energy and at a minimum cost.
3. All possible sources of variation in die friction and wafering energy have not yet been analyzed. The effects due to the remaining factors should be studied on a laboratory- and an industrial-scale extrusion process. Information on die temperatures and the application of steam or water prior to wafering appears to be most vital.
4. There are many conflicts between the forage harvesting, dehydrating and wafering processes as far as energy requirements and operating expenses are concerned. An analysis of the entire operation should be carried out to minimize energy and still maintain a profit for each stage of the operation.
5. Many wafers, made in this experiment, displayed good durability but their density was visibly poor. For a meaningful representation of wafer quality both density and durability should be included in future research.

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APPENDIX A: A SAMPLE CALCULATION OF WAFERING ENERGY.

The following calculations were performed on the data obtained from the treatment containing current year alfalfa (R_2) at 30 percent moisture (M_3) with the binder Orzan (B_1) added. The extrusion pressure was 3400 psi (U_2) and the back pressure was at its high level of 3000 psi (L_2).

The area under the total pressure-displacement curve,

$$A_t = 42.0 \text{ cm}^2$$

The area under the extrusion portion of the pressure-displacement curve,

$$A_e = 40.7 \text{ cm}^2$$

The area under the compression portion of the pressure-displacement curve,

$$A_c = A_t - A_e$$

$$= 1.3 \text{ cm}^2/\text{wafer}$$

The area corresponding to the extrusion of one wafer,

$$A_{e/w} = \frac{(\text{wafer length in die}) \times A_e}{(\text{active die length})},$$

where wafer length = 1.20 inches (see Table 2.)

and die length = 9 inches (constant)

$$A_{e/w} = 5.4 \text{ cm}^2/\text{wafer}$$

<u>1 cm^2/wafer</u> corresponds to (133.3 psi of cylinder pressure x 1.0 inch of ram displacement) / wafer

or (5.6 x 133.3 psi of extrusion pressure x 1.0 inch of ram displacement) / wafer

(where 5.6 equals the ratio of cylinder area to die area)

or (1.23 sq in x 746.5 psi x 1 inch) / wafer

(where 1.23 sq in equals the die area)

or 918 in-lb/wafer

APPENDIX A: Continued

or 386×10^{-7} hp-hr/wafer

or 386×10^{-7} hp-hr/283×10^{-7} tons

(where 283×10^{-7} tons (25.7 gms) equals the wafer weight from Table 1 for this treatment)

or 1.36 hp-hr/ton of wafers

So for this treatment:

the compression energy, $E_c = A_{c/w} \times 1.36$ hp-hr/ton

$= 1.77$ hp-hr/ton of wafers

the extrusion energy, $E_e = A_{e/w} \times 1.36$ hp-hr/ton

$= 7.38$ hp-hr/ton of wafers

and the total wafering energy, $E_t = E_c + E_e$

$= 9.15$ hp-hr/ton of wafers

APPENDIX B: WAFERING ENERGY* DATA.

Replicate - R_1 (one year old alfalfa)

Binder - B_0 (none)

Extrusion Pressure (psi)	Back Pressure (psi)	Moisture Content (percent)	Compression Energy	Extrusion Energy	Total Energy
(U_1) 1100	(L_1) 350	(M_1) 10	2.24	3.33	5.57
		(M_2) 20	1.99	3.13	5.12
		(M_3) 30	2.15	2.81	4.96
	(L_2) 750	10	2.07	3.46	5.53
		20	3.07	3.54	6.61
		30	2.03	2.62	4.65
(U_2) 3400	2200	10	4.31	7.96	12.27
		20	3.68	7.61	11.29
		30	2.29	7.54	9.83
	3000	10	4.31	8.55	12.86
		20	3.53	8.13	11.66
		30	3.23	7.54	10.77
(U_3) 5800	4500	10	6.55	10.79	17.34
		20	5.06	10.81	15.87
		30	3.23	10.59	13.82
	5100	10	6.90	10.84	17.74
		20	4.91	10.81	15.72
		30	3.49	10.65	14.14

* Measured in horsepower-hours per ton of wafers

APPENDIX B: Continued

Replicate - R_1 (one year old alfalfa)

Binder - B_1 (Orzan)

Extrusion Pressure (psi)	Back Pressure (psi)	Moisture Content (percent)	Compression Energy	Extrusion Energy	Total Energy
1100	350	10	2.59	3.57	6.16
		20	3.53	3.41	6.94
		30	1.89	2.75	4.64
	750	10	2.42	3.53	5.95
		20	2.61	3.24	5.85
		30	2.69	2.66	5.35
3400	2200	10	4.83	8.30	13.13
		20	4.76	7.89	12.65
		30	2.82	7.10	9.92
	3000	10	6.90	8.68	15.58
		20	4.60	8.42	13.02
		30	3.49	7.49	10.98
5800	4500	10	6.55	10.96	17.51
		20	4.60	11.01	15.61
		30	2.82	10.44	13.26
	5100	10	6.72	10.99	17.71
		20	5.98	10.81	16.79
		30	3.36	10.65	14.01

APPENDIX B: Continued

Replicate - R_1 (one year old alfalfa)

Binder - B_2 (Bentonite)

Extrusion Pressure (psi)	Back Pressure (psi)	Moisture Content (percent)	Compression Energy	Extrusion Energy	Total Energy
1100	350	10	1.38	3.43	4.81
		20	2.31	3.12	5.43
		30	2.15	2.81	4.96
	750	10	3.28	3.36	6.64
		20	2.15	3.00	5.15
		30	2.56	2.66	5.22
3400	2200	10	2.76	8.17	10.93
		20	3.37	7.68	11.05
		30	3.77	7.15	10.92
	3000	10	5.52	8.65	14.17
		20	4.30	8.42	12.72
		30	2.56	7.53	10.09
5800	4500	10	6.21	10.89	17.10
		20	3.68	10.84	14.52
		30	3.23	10.58	13.81
	5100	10	6.55	10.84	17.39
		20	3.84	10.88	14.72
		30	1.75	10.58	12.33

APPENDIX B: Continued

Replicate - R_2 (current year alfalfa)
Binder - B_0 (none)

Extrusion Pressure (psi)	Back Pressure (psi)	Moisture Content (percent)	Compression Energy	Extrusion Energy	Total Energy
1100	350	10	2.24	3.57	5.81
		20	1.54	3.03	4.57
		30	.94	2.57	3.51
	750	10	1.73	3.38	5.11
		20	1.84	3.04	4.88
		30	1.75	2.53	4.28
3400	2200	10	3.79	8.10	11.89
		20	2.92	7.62	10.54
		30	1.48	6.86	8.34
	3000	10	4.31	8.70	13.01
		20	3.07	8.22	11.29
		30	1.35	7.36	8.71
5800	4500	10	5.69	10.85	16.54
		20	2.31	11.09	13.40
		30	1.61	10.05	11.66
	5100	10	4.14	10.92	15.06
		20	2.61	10.93	13.54
		30	1.35	10.47	11.82

APPENDIX B: Continued

Replicate - R_2 (current year alfalfa)

Binder - B_1 (Orzan)

Extrusion Pressure (psi)	Back Pressure (psi)	Moisture Content (percent)	Compression Energy	Extrusion Energy	Total Energy
1100	350	10	1.21	3.53	4.74
		20	1.99	3.24	5.23
		30	1.61	2.54	4.15
	750	10	3.28	3.70	6.98
		20	2.46	2.95	5.41
		30	1.35	2.54	3.89
3400	2200	10	4.14	8.13	12.27
		20	1.84	7.74	9.58
		30	1.21	6.77	7.98
	3000	10	2.59	8.94	11.53
		20	3.22	8.06	11.28
		30	1.77	7.38	9.15
5800	4500	10	4.48	11.03	15.51
		20	3.22	10.64	13.86
		30	1.89	10.16	12.05
	5100	10	5.52	11.34	16.86
		20	3.84	10.65	14.49
		30	1.75	10.41	12.16

APPENDIX B: Continued

Replicate - R_2 (current year alfalfa)

Binder - B_2 (Bentonite)

Extrusion Pressure (psi)	Back Pressure (psi)	Moisture Content (percent)	Compression Energy	Extrusion Energy	Total Energy
1100	350	10	2.24	3.43	5.67
		20	1.84	3.08	4.92
		30	1.35	2.57	3.92
	750	10	2.42	3.65	6.07
		20	1.54	3.04	4.58
		30	2.43	2.60	5.03
3400	2200	10	4.31	7.86	12.17
		20	4.45	7.15	11.60
		30	1.75	6.05	7.80
	3000	10	3.45	8.41	11.86
		20	3.68	7.97	11.65
		30	2.02	7.11	9.13
5800	4500	10	3.79	10.75	14.54
		20	1.54	10.52	12.06
		30	3.90	10.02	13.92
	5100	10	4.83	10.73	15.56
		20	2.77	10.58	13.35
		30	2.29	10.35	12.64

APPENDIX C: EXTRUSION TIME[t], DURABILITY RATING[d] AND WAFERING EFFICIENCY[e] DATA.

Replicate - R_1 (one year old alfalfa)

Binder - B_0 (none)

Extrusion Pressure (psi)	Back Pressure (psi)	Moisture Content (percent)	Extrusion Time	Durability Rating	Wafering Efficiency (x 10)
(U_1) 1100	(L_1) 350	(M_1) 10	3.44	57.0	.98
		(M_2) 20	3.24	97.0	.53
		(M_3) 30	3.76	83.2	.60
	(L_2) 750	10	5.50	73.2	.76
		20	6.08	97.8	.68
		30	7.18	90.4	.51
(U_2) 3400	2200	10	3.13	95.9	1.28
		20	3.28	99.1	1.14
		30	3.38	91.0	1.08
	3000	10	6.25	95.8	1.34
		20	14.26	99.2	1.18
		30	6.43	94.2	1.14
(U_3) 5800	4500	10	3.65	97.0	1.79
		20	3.26	99.2	1.60
		30	3.45	96.1	1.44
	5100	10	5.86	98.4	1.80
		20	16.91	99.0	1.59
		30	6.83	95.8	1.48

[t] - Measured in seconds

[d] - Measured in percent

[e] - Measured in horsepower-hours per ton per change in durability rating

APPENDIX C: Continued

Replicate - R_1 (one year old alfalfa)

Binder - B_1 (Orzan)

Extrusion Pressure (psi)	Back Pressure (psi)	Moisture Content (percent)	Extrusion Time	Durability Rating	Wafering Efficiency (x 10)
1100	350	10	3.41	94.4	.65
		20	3.60	97.8	.71
		30	3.34	84.3	.55
	750	10	6.39	96.6	.62
		20	7.15	98.3	.60
		30	6.50	83.7	.64
3400	2200	10	3.49	98.6	1.33
		20	3.46	98.9	1.28
		30	3.17	91.8	1.08
	3000	10	13.28	99.1	1.57
		20	7.06	99.1	1.31
		30	5.65	87.2	1.26
5800	4500	10	3.43	99.0	1.77
		20	3.39	98.9	1.58
		30	3.10	88.4	1.50
	5100	10	43.22	99.5	1.78
		20	9.57	99.0	1.70
		30	5.39	90.3	1.55

APPENDIX C: Continued

Replicate - R_1 (one year old alfalfa)
Binder - B_2 (Bentonite)

Extrusion Pressure (psi)	Back Pressure (psi)	Moisture Content (percent)	Extrusion Time	Durability Rating	Wafering Efficiency (x 10)
1100	350	10	3.15	57.7	.83
		20	3.23	96.9	.56
		30	3.65	91.1	.54
	750	10	5.35	76.7	.87
		20	6.30	96.6	.53
		30	6.18	86.4	.60
3400	2200	10	3.11	96.8	1.13
		20	3.44	99.0	1.12
		30	3.15	93.4	1.17
	3000	10	5.31	97.4	1.45
		20	15.32	99.1	1.28
		30	5.81	95.6	1.06
5800	4500	10	3.16	98.1	1.74
		20	3.10	99.0	1.47
		30	3.09	95.5	1.45
	5100	10	11.12	98.5	1.77
		20	35.28	99.1	1.49
		30	6.04	91.8	1.34

APPENDIX C: Continued

Replicate - R_2 (current year alfalfa)

Binder - B_0 (none)

Extrusion Pressure (psi)	Back Pressure (psi)	Moisture Content (percent)	Extrusion Time	Durability Rating	Wafering Efficiency (x 10)
1100	350	10	3.32	22.6	2.57
		20	3.17	92.3	.50
		30	3.28	64.1	.55
	750	10	5.60	48.5	1.05
		20	5.72	92.5	.53
		30	5.43	78.8	.54
3400	2200	10	3.09	89.8	1.32
		20	3.21	98.6	1.07
		30	3.03	84.0	.99
	3000	10	5.64	96.5	1.35
		20	7.40	98.9	1.14
		30	5.00	83.8	1.04
5800	4500	10	3.23	96.8	1.71
		20	3.40	98.4	1.36
		30	3.14	83.5	1.40
	5100	10	8.30	98.0	1.54
		20	10.24	98.6	1.37
		30	5.47	78.7	1.50

APPENDIX C: Continued

Replicate - R_2 (current year alfalfa)
Binder - B_1 (Orzan)

Extrusion Pressure (psi)	Back Pressure (psi)	Moisture Content (percent)	Extrusion Time	Durability Rating	Wafering Efficiency (x 10)
1100	350	10	3.57	89.8	.53
		20	3.62	98.2	.53
		30	3.35	77.3	.54
	750	10	8.05	96.8	.72
		20	7.15	98.7	.55
		30	6.06	80.1	.49
3400	2200	10	3.52	98.7	1.24
		20	3.24	98.7	.97
		30	3.19	87.0	.92
	3000	10	18.26	99.2	1.16
		20	6.77	98.4	1.15
		30	5.24	81.9	1.11
5800	4500	10	3.44	98.9	1.57
		20	3.36	98.1	1.41
		30	3.23	87.4	1.38
	5100	10	49.61	99.4	1.70
		20	7.93	98.2	1.48
		30	5.23	87.2	1.39

APPENDIX C: Continued

Replicate - R_2 (current year alfalfa)

Binder - B_2 (Bentonite)

Extrusion Pressure (psi)	Back Pressure (psi)	Moisture Content (percent)	Extrusion Time	Durability Rating	Wafering Efficiency (x 10)
1100	350	10	3.52	89.4	.63
		20	3.63	97.3	.51
		30	3.40	78.3	.50
	750	10	6.56	92.4	.66
		20	6.77	98.4	.47
		30	5.70	83.6	.60
3400	2200	10	3.22	98.4	1.24
		20	3.32	98.8	1.17
		30	3.11	91.3	.85
	3000	10	7.67	98.9	1.20
		20	7.96	98.9	1.18
		30	5.19	89.5	1.02
5800	4500	10	3.28	98.7	1.47
		20	3.13	98.8	1.22
		30	3.17	85.4	1.63
	5100	10	14.54	99.1	1.57
		20	9.11	98.8	1.35
		30	5.46	92.3	1.37

APPENDIX D: TABLE OF ANALYSIS OF VARIANCE FOR DURABILITY RATING[1].

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	F-Ratio	Probability
R	165.4	1	165.4	1.26	0.3781
B	634.5	2	317.2	2.42	0.2924
Error "1" BR	262.2	2	131.1		
M	1493.0	2	746.5	15.35	0.0001 ***
U	2221.0	2	1110.5	22.83	0.0000 ***
MU	1500.0	4	375.0	7.71	0.0004 ***
MB	710.7	4	177.7	3.65	0.0184 *
UB	828.8	4	207.2	4.26	0.0096 **
MUB	849.8	8	106.2	2.18	0.0665
Error "2"	1167.2	24	48.6		

[1] To ensure that the unwanted effect due to widely varying extrusion times was not interfering with the analysis, only data obtained with low back pressure (fairly constant extrusion times) were used.

* Significant at the 5 % probability level
** Significant at the 1 % probability level
*** Significant at the 0.1 % probability level